Traffic channelisation and pavement deterioration: An investigation of the lateral wander on asphalt pavement rutting

By

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The thesis is submitted in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy of the University of Portsmouth

April 2020

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United Kingdom

Abstract

Traffic loading is the primary factor considered when designing a pavement. Accurate estimation of traffic load plays a crucial role in the economical design of pavements. The cross-sectional distribution of the vehicle positions means that the traffic load is spread across the surface of the pavement. It is suggested in some design guides that the spread of the traffic load across the pavement surface should be considered alongside the standard axle loading the pavement will need to carry over its lifespan. Several factors influence the distribution of vehicle positions and hence load. However, there is little guidance on how to predict the spread of traffic loads when designing a new pavement, and empirical studies supporting any such guidance is also limited. When wheel paths are perfectly aligned with each other, this is termed channelised traffic (or channelisation). The first part of this research addressed this gap through analyses of data collected on the vehicle positions at 100 sections of pavement in Portsmouth, United Kingdom. The analyses, found a positive linear association between the degree of lateral wander and both the lane width and road width. These results suggest that the use of a binary measure of vehicle position used in the UK design guidance may not be suitable. The results also highlight the importance of both lane and road width, contrary to the existing body of research that indicates only one or the other to be a determinant of vehicle position. The second part of this research focused on investigating the impact of channelisation on asphalt pavement rutting. Regression analysis was conducted to understand how the degree of channelisation influenced the rut depths that the traffic loading had created. The analyses revealed that the degree of channelisation of traffic has a statistically significant contribution to the progress of rutting. In this study, the difference between the maximum and minimum degrees of channelisation observed, related to a seven-fold difference in the rut depth. The last part of this research aimed to combine these findings to suggest ways of considering road geometry to produce a channelisation factor to be incorporated

into the calculation of the traffic load for pavement design. This was achieved by combining the two predictive equations developed from regression analyses.

These findings have practical contributions to give further guidance to pavement engineers when designing new pavements and considering the maintenance schedules for existing pavements, as it allows them to better predict the future condition and lifespan of a pavements.

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Abbreviations

AADT	Annual Average Daily Traffic
AV	Autonomous Vehicle
AVCS	Automated Vehicle Control Systems
DMRB	Design Manual for Roads and Bridges
ESAL	Equivalent Standard Axle Load
FWD	Falling Weight Deflectometer
HVC	Heavy Commercial Vehicle
HVS	Heavy Vehicle Simulations
HD	High Definition
HMA	Hot Mix Asphalt
HBM	Hydraulically Bound Materials
ICE	The Institution of Civil Engineers
IRI	International Roughness Index
K-S	Kolmogorov-Smirnov
PMS	Pavement Management System
PFI	Private Finance Initiative
SCANNER	Surface Condition Assessment for the National Network of Roads
SCRIM	Sideway-force Coefficient Routine Investigation Machine
TRACS	Traffic-Speed Condition Surveys
UK	United Kingdom
VOC	Vehicle Operating Cost

Declaration

This thesis was conducted at the University of Portsmouth, School of Civil Engineering between February 2017 and April 2020. I declare that this represents the original work and contribution of the author, except as acknowledged by the general and specific references.

I hereby certify that this has not been submitted for a degree of another university.

Renan Sinanmis

Acknowledgments

Firstly, I would like to express my sincere gratitude to my first supervisor Dr Lee Woods for the continuous support of my PhD study and related research, for his patience, motivation and immense knowledge. His guidance of helping me all the time of research and writing of this thesis are deeply appreciated.

I would like to thank the rest of my PhD supervisory team Dr Stephanie Barnett and Dr Nikos Nanos for their encouragement. Appreciation and thanks are also due to Dr Rebecca Lodwick, senior teaching fellow Samuel Leung, and graduated undergrad student Kyle Shoesmith, who provided help and assistance.

My sincere thanks also go to Portsmouth City Council and its Highways contractor COLAS Ltd., who provided and gave access to the secondary data of this research.

Appreciation and thanks are also due to Dr Mohammed Ali the internal examiner and Dr Neil Ferguson who has agreed to be the external examiner of this research.

Acknowledgments is due to the Civil Engineering Department at the University of Portsmouth for providing the facilities to carry out this research.

Acknowledgments is also due to my colleagues in the School of Civil Engineering and Surveying providing me help and support throughout the research period of this study.

Appreciation and thanks also due to the Turkish Government who sponsored me to pursue my research.

Last but not the least, I would like to thank my family: my husband, my parents and my sister for supporting me spiritually throughout conduction this research and my life in general.

List of Publications

[1] Sinanmis, R., & Woods, L. (2018). Investigation into the Pavement Condition Rating (PCR) of selected roads in a Nottingham case study. London: 50th Universities' Transport Study Group Conference: UTSG.

[2] Sinanmis, R., & Woods, L. (2019). Relationship between channelisation and geometric characteristics of road pavements. *International Journal of Pavement Engineering*, 1-8. doi: 10.1080/10298436.2019.1696463.

[3] Sinanmis, R. and Woods, L., (2020). Traffic channelisation and pavement deterioration: An investigation of the role of lateral wander on asphalt pavement rutting. *Road Materials and Pavement Design.* (Under review)

Chapter 1 Introduction

This chapter provides a general overview of the research investigated. It starts with the background of the study and based on the background, the research gap is defined. In order to be able to fill this gap, the aims and objectives are presented. The final part outlines the structure of the thesis.

1.1.Research Background

Highway pavements provide the transport network for most travel undertaken in the world, and provide the space for various other activities to take place . Key to ensuring the performance of a pavement is predicting the stresses, strains and weather conditions that the pavement will need to endure over its lifespan. A large body of literature has found many factors that influence the deterioration, and hence lifespan, of pavements. The key determinant has been found to be the amount and type of traffic exerting a load on the pavement surface (Atkinson, Merrill, & Thom, 2006; Blab & Litzka, 1995; Buiter, Cortenraad, van Eck, & van Rij, 1989). Hence, various design standards and guides convert different vehicle types into standard axle loads and wear factors. In the United Kingdom (UK), the wear factors specified in the design standard (Highways Agency, 2006b) are derived from the fourth power law, where the damaging effect is proportional to the fourth power of the load exerted by a vehicle's wheel onto the surface. It should be noted that other studies have suggested a value larger than 7 could be applicable depending on the pavement type and expected traffic (A. R. Dawson, 2008; Dormon & Metcalf, 1965; Jameson, 1996). Studies and design codes around the world highlight that load repetitions by heavy vehicles especially results in considerable deterioration (Collop, 2002; Erlingsson, Said, & McGarvey, 2012). Whilst there is a large body of evidence as to the damaging effect of different vehicle types on pavements, there is less evidence and guidance as to whether the distribution of traffic loads over the cross section of the pavement influences this, and less still on how the cross sectional spread of loading should be predicted. The spread in the position of vehicles across a pavement surface is referred to as ‘lateral wander’. In instances where there is very little lateral wander, the traffic can be referred to as ‘channelised’. In channelised traffic, successive vehicles follow the same wheel path over a narrower section of the pavement surface. Channelised traffic might be expected at narrow sections of pavement such as traffic calming gateways, bus stops or car parks (Walsh et al., 2011a). Channelised traffic is usually considered to have a more detrimental impact on the pavement than traffic with a high degree of a lateral wander (Walsh et al., 2011a). In the past, several methods have been used to measure the lateral position of vehicles (Blab & Litzka, 1995; Buiter et al., 1989; Erlingsson et al., 2012; Liu & Wang, 2003; Luo & Wang, 2013; Siddharthan, Nasimifar, Tan, & Hajj, 2017; Timm & Priest, 2005). These measurements have been analysed to find the most important parameters influencing the lateral position of vehicles in a lane/road. However, little evidence exists as to how to categorise traffic flow as either channelised or not when designing a pavement in the UK. In addition, those studies cited here tend to be based on either theoretical models or laboratory experiments. Field observations are likely to give a better representation of actual driving behaviours and none have been found that are applicable to the UK. Therefore, this study firstly aims to address this gap in knowledge and provide guidance to practitioners in the UK.

Some design guides account for the effects of channelisation by increasing the traffic loading predicted to be carried by the pavement over its lifespan (Garrett, 1983; Walsh et al., 2011a). The UK design standards (Highways Agency, 2006b), do not consider channelisation effects, however, several widely used supplementary design guides do. The Institution of Civil Engineers (ICE) design guidance suggests doubling the design traffic when channelisation is expected, to prevent premature deterioration (Walsh et al., 2011b). There is little empirical evidence that channelisation leads to double the traffic load or double the rate of pavement deterioration. The recommendation stems from a study conducted by Kent County Council in 1983 (Garrett, 1983). The rationale for the factor of two (doubling) appears to be based on a theoretical consideration of a normal distribution of vehicle positions on a wide lane and narrow lane.

The channelisation issue of traffic needs to be investigated further in order to design the pavements with stronger materials or thicker layers to avoid premature deterioration. Such deterioration could include surface cracking, loss of texture, and in the case of flexible asphalt pavements, severe rutting. Deterioration of pavements is a safety concern and rutting in asphalt pavements is a trigger in Pavement Management Systems (PMS) for maintenance to be undertaken (Robinson, Danielson, & Snaith, 1998).

Whilst there appears to be a considerable body of literature and design guides that indicate channelisation causes rutting, the results of these studies vary and are rarely supported by field measurements. Therefore, this study secondly sought to provide further evidence as to the effects of channelised traffic on asphalt pavement rut depths in the UK.

Finally, the results of first and second steps were then combined to be able to produce a channelisation factor in terms of road geometry parameters for pavement engineers to modify pavement thicknesses more appropriately when designing a new asphalt pavement.

1.2.Statement of purpose and problem

Following a review of the literatures, there is little guidance that explains how to categorise the traffic flow as either channelised or not channelised. This may lead to incorrect estimates of the design traffic which is potentially compounded by a lack of certainty over the damaging effect of this traffic if it is considered to be channelised. Although this problem is highlighted by Kent County Council (Garrett, 1983) and later supported by ICE design guidance (Walsh et al., 2011a), the evidence base for considering vehicle wander as binary (either channelised or unchannelised) and the factor of ‘2’ multiplied to the design traffic when it is channelised. At the moment, the evidence base for this relationship is very weak and needs to be stronger. This study aims to provide new guidance based on consideration of the actual distributions of the wheel loads observed in reality rather than a theoretical supposition. This increased loading associated with lateral wander is also considered in international design standards with ‘lane width’ being used a proxy for the degree of channelisation/lateral wander such as in Germany, Austria, and the Netherlands (Atkinson et al., 2006; Blab & Litzka, 1995; Sieber, 2012). Similarly, there is little in the way of evidence supporting these relationships in real world conditions. Whilst there is experimental (lab-based) and simulation (models) evidence to support these relationships, there is little empirical (observed in the field) research to confirm these relationships. Moreover, pavement designs, materials, maximum vehicle loading, weather conditions, maintenance regimes and soil conditions vary significantly between countries as diverse as the Netherlands, Austria, the USA, Sweden, Finland and South Africa where other relationships have been suggested, compared to the UK. Accordingly, relationships between channelisation and pavement deterioration found in one country might not be the same as in the UK. The importance of studying channelisation and treatment of vehicle wander is to reduce pavement damage to ensure it reaches the specified design life by varying the pavement thickness or strength of materials used.

1.3.Research aims and objectives

The overall aim of the research is to investigate the effect of channelisation on the performance of flexible (asphalt) pavements, currently and in the future, so that highway authorities can make better-informed decisions regarding pavement design and management.

The following specific objectives were pursued to achieve the overall aims.

1. Determine the relationship between channelisation and road geometry.
2. Investigate the impact of channelisation on asphalt pavement rutting.
3. Suggest ways in which current pavement design guidance and PMSs could be enhanced to better account for channelisation in the future.

1.4.Scope of the study

This research was held in Portsmouth only. The pavement type studied was a flexible asphalt pavement. In terms of the pavement performance, the rutting damage of pavement deterioration was analysed throughout the research to demonstrate the channelisation impact rather than any other deterioration modes.

1.5.Structure of the thesis

This thesis consists of 6 chapters. Chapter 1 is an introduction chapter where the general background of the research is presented and the problem statement is discussed. The research aims and objectives are also stated.

The types of pavements, categories of pavement defects and the damaging effects of traffic, specifically, the channelisation of traffic and a general overview of the PMS are reviewed in Chapter 2.

In Chapter 3, the research methodology is addressed in detail and the pilot studies that were conducted are described.

Chapter 4 presents the process of the data collection and collation.

Chapter 5 gives an analysis of both primary and secondary data to develop models.

Finally, Chapter 6 discusses the results compared to each objective, draws conclusions, notes the limitations of the work and recommends further work that could be undertaken into the topic.

1.6.Chapter Summary

This chapter aimed to highlight the significant contribution of considering the impact of channelisation on pavement design and management. Based on the statement of the problem, research aims and objectives were presented; the thesis structure was also stated.

Chapter 2 Literature Review

2.1. Introduction

This chapter is a review of the literature about road pavements and design considerations. The next section explains road pavement types, followed by the deterioration of flexible pavements. Later, the reasons for deterioration are critically evaluated with a specific focus on channelisation of pavement sections. The final section reviews pavement management systems and considerations.

2.2. Road pavement functions and types

Road pavements are layered structures positioned over natural soil to support wheel loads of different magnitudes, speeds and intervals. Each layer of the structure should have adequate strength to distribute the traffic loads over a wide enough area that underlying soil (subgrade) can carry, as shown in Figure 2.1 (Wignall, Kendrick, Ancill, & Copson, 1999). The primary functions of a pavement structure are (Walsh et al., 2011b):

- To produce a safe, smooth and comfortable riding surface even at high speed
- To give adequate coefficient friction for a safer running surface for traffic under all conditions
- To provide adequate surface impervious to water penetration
- To prevent frost damage to frost susceptible subgrades by sufficient construction thickness
- To provide a dustproof surface so that traffic safety is not impaired by reduced visibility
- To produce the least noise from moving vehicles

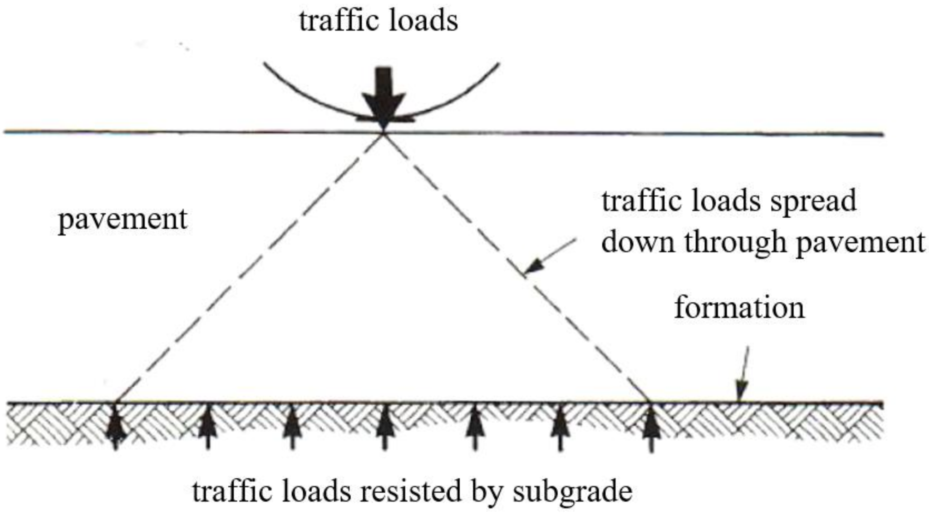


Figure 2. 1 Distribution of load through the road pavement structure (Wignall et al., 1999)

Roads have evolved over the centuries from Roman and earlier pavements through to the modern pavements used today (Fullalove, 2015). The design of pavements varies depending on different conditions of soil, environment, weather and climate. In general terms, road pavements can be classified into three main types depending on the structure: flexible, composite and rigid pavements, as shown in Figure 2.2.

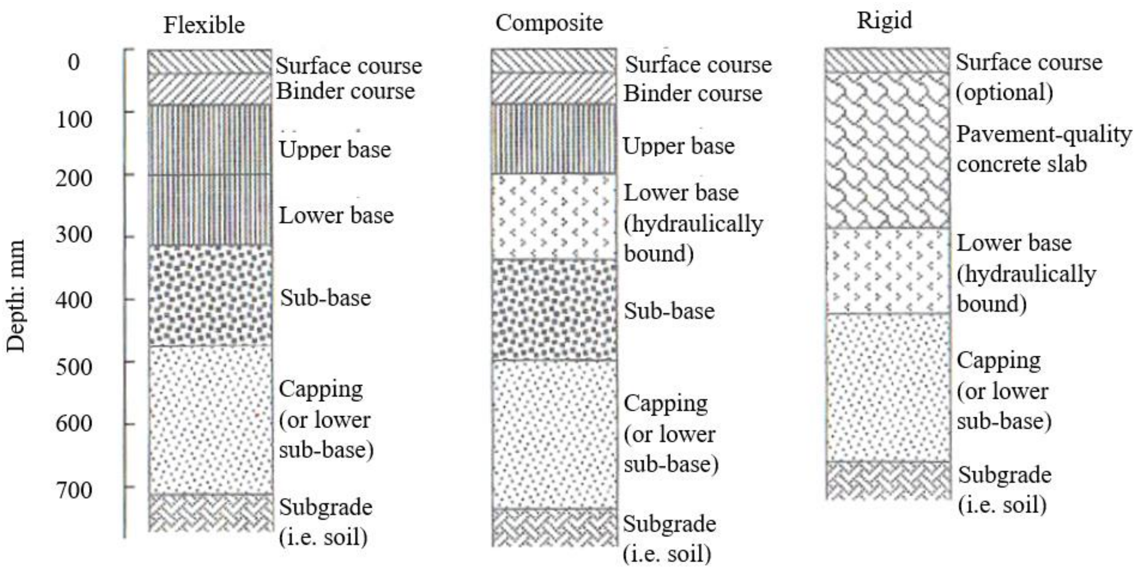


Figure 2. 2 Basic elements of flexible, flexible composite and rigid pavements (Hughes & O'Flaherty, 2015)

2.2.1. Flexible pavements

A flexible road pavement consists of layers of unbound materials and asphalt (aggregate and flexible binder) that are topped by a surface layer that is commonly aggregate bound with bitumen (previusly also tar) (Hughes & O'Flaherty, 2015; Wang, 2011). The surface layer provides a safe surface for traffic to operate on in terms of offering adequate skid resistance, low noise and minimal surface spray in wet weather (Brown, 2013). It also resists cracking and rutting and protects the underlying structure, thus minimising the required maintenance (Hughes & O'Flaherty, 2015).

The binder course provides a good riding quality and distributes the applied traffic loads to the base. On lightly trafficked roads, the binder course may be omitted, however, on heavily trafficked roads it is commonly laid below the surface course (Hughes & O'Flaherty, 2015). Underneath the binder course, the base layer is the main structure to distribute the load so that the strength capacities of the lower layers are not exceeded.

The subbase course is the last layer used to spread the load to the subgrade (soil). It is made up of compacted, but freely draining aggregate. This prevents water from penetrating the layers, which can cause a loss of pavement strength. When the subgrade is weak, an additional layer may be used called ‘capping’. The final layer, which is natural soil, is called subgrade and can be in the form of compacted natural soil or stabilised soil with cement, lime or other materials (Hughes & O'Flaherty, 2015).

Since the whole flexible pavement structure bends or deflects due to traffic loads, all the layers that compose the structure generally need to accommodate the ‘flexing’ effect.

There are three common types of Hot Mix Asphalt (HMA) used in flexible pavements, as shown in Figure 2.3. These are Dense-Graded Mixes, Stone Matrix Asphalt Mixes and Open-Graded Mixes.

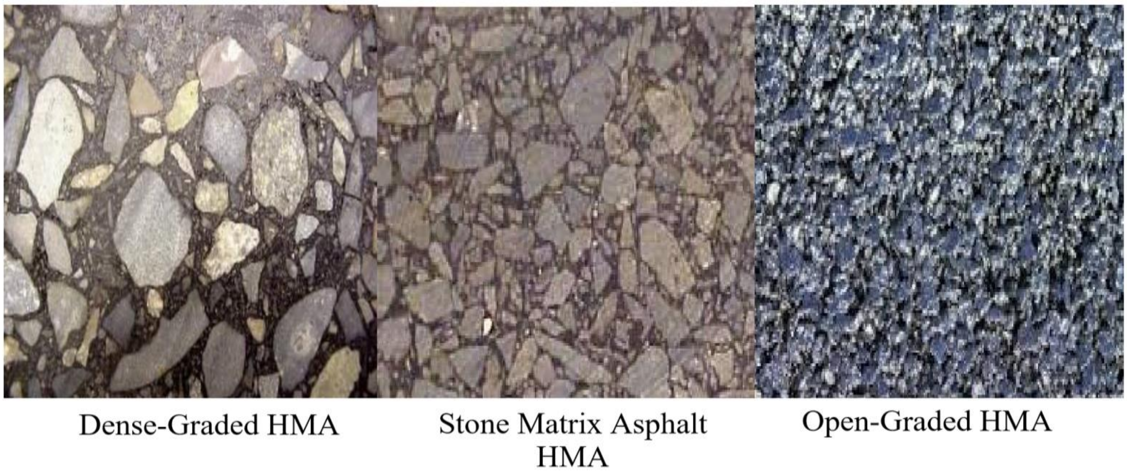


Figure 2. 3 Different types of Hot Mix Asphalt (HMA) in Flexible Pavement (Thom, 2015)

The advantages of using HMA are ease of construction and lower cost. The HMA maintenance is more straightforward in terms of the type of maintenance that can be used such as sealing coats, repairing cracks or resurfacing.

2.2.2. Rigid pavements

The main feature of a typical rigid pavement is that it has a cement concrete slab with high flexural strength as the main structural layer (Hughes & O'Flaherty, 2015). The concrete may be reinforced with steel (Rogers, 2008).

The surface course or concrete slab is designed to allow traffic to run directly on its surface and provide a smooth, comfortable ride with good skid resistance under all weather conditions (Hughes & O'Flaherty, 2015).

As there is only one layer between the concrete slab and subgrade called the subbase (Mohod & Kadam, 2016). The subbase layer is intended to provide uniform, stable and permanent support for the concrete slab particularly when subgrade damage is anticipated from frost action, poor drainage, construction traffic or mud-pumping (Hughes & O'Flaherty, 2015).

The subgrade (with capping layer if necessary) is the even and compacted natural soil for keeping uniform support preventing pavement distortion.

There are four main categories of rigid pavement as follows (Mohod & Kadam, 2016):

- Jointed plain concrete pavement (JPCP)
- Jointed reinforced concrete pavement (JRCP)
- Continuous reinforced concrete pavement (CRCP)
- Pre-stressed concrete pavement (PCP)

In the UK, currently, the preferred rigid pavement construction types are either CRCP with eliminated joints achieved by reinforcement in the continuous reinforced concrete structure and asphalt overlay of minimum thickness 30 mm or CRCB (Continuously reinforced concrete base) with an asphalt overlay of 100 mm (Highways Agency, 2006b; Hughes & O'Flaherty, 2015).

The lifespan of rigid pavements tends to be longer than flexible pavements and they require less maintenance. However, the initial cost is higher and when maintenance is undertaken, this is often very costly compared to asphalt pavements. The flexibility of the overall structure of rigid pavements is not as resilient to conditions such as extreme pressure and extreme temperature.

2.2.3. Composite pavements

Composite pavements contain layers of Hydraulically Bound Materials (aggregates and cement) combined with flexible asphalt layers giving HBM some benefits of each. Upper base courses are formed from bitumen-bound materials with a layer of asphalt on top and are supported on a subbase/foundation (Hughes & O'Flaherty, 2015).

2.3. Types of flexible pavement deterioration

Flexible pavements can deteriorate in a number of ways affecting one or more of the different layers or subgrades.

Research has indicated that there are four major categories of common flexible surface deteriorations. These are cracking, surface deformation, disintegration and surface defects (Adlinge & Gupta, 2013).

Common modes of flexible pavement failure include rutting, fatigue cracking and thermal cracking in the UK (Highways Agency, 2008). As shown in Figure 2.4, rutting is defined as a depression or groove worn into pavement surfaces by the vehicle wheels. A very narrow rut indicates a surface failure, whereas a wide rut indicates a subgrade or subbase failure. Minor surface rutting can be maintained by filling with micro-paving or paver-placed surface over the shim. However, the deeper ruts may need to be shimmed with a truing and levelling course, with an overlay placed over the shim. Reconstruction may be required when the failure is in the subgrade layer (Adlinge & Gupta, 2013).

Figure 2. 4 Illustration of rutting mechanism (A. Dawson & Kolisoja, 2006)

Fatigue cracking (also known as alligator cracking) is a multiple of interconnected cracks creating small and irregular shaped pieces of pavement. As shown in Figure 2.5, it causes disintegration of the surface. When the phenomenon is developed, it results in potholes. They are usually associated with base or drainage problems. Minor alligator cracks may be repaired with a patch or area repair. However, significant defects require reconstruction (Adlinge & Gupta, 2013).

Figure 2. 5 High severity fatigue cracking (Adlinge & Gupta, 2013)

Thermal cracking is prominent distress in regions with low temperatures and/or high rates of temperature drop (Dave & Hoplin, 2015). Stresses are built up until they exceed the strength of the material, leading to the formation of cracks (Teltayev & Radovskiy, 2018).

The surfaces of all pavements eventually suffer from loss of skid-resistance due to the nature of the friction generated between vehicles' tyres and the road surface (Viner, Sinhal, & Parry, 2005).

2.4. Reasons for flexible pavement deterioration

The overall stability of flexible pavements depends on various combinations of traffic loadings and varying environmental conditions (Wayessa & Abuye, 2019). The structural deterioration may develop in the pavement over time and eventually reach failure condition (Brown, 2013).

There are essentially five fundamental causes of failure relating to pavements, with a degree of interdependence (Hong & Prozzi, 2006; Pearson, 2011);

- Inadequate bearing capacity of subgrade – Happens where the effect of the applied load over-stresses the subgrade.
- Failure due to frost damage – Usually related to ingress of moisture into the pavement which then expands when frozen.
- Failure of constituent materials due to environmental exposure – Due to the effect of ultraviolet radiation and oxygenation and the effects of moisture within the pavement in non-freezing conditions.
- Inadequate quality of construction

Improper pavement design is the primary reason for the premature deterioration in some developing countries, in contrast, in the UK it is mainly higher traffic loading and environmental factors (Brown, Thom, & Hakim, 2004; Highways Agency, 2008; Zumrawi, 2015). As bitumen is a visco-elastic material, the risk of accumulation of permanent deformation in the surfacing (non-structural rutting) is expected and may increase during periods of hot weather and is further exacerbated by slow-moving and/or stationary traffic (Highways Agency, 2008). However, in the UK it is less common than seasonal changes in moisture levels and the action of a freeze-thaw cycle, particularly on cracked pavements of thin construction.

2.4.1. Traffic loading

Traffic loading is a significant factor in terms of pavement design and maintenance planning strategies. Forecasting traffic load accurately affects the structural design of the upper layers of road pavement. In the UK it is currently predicted according to the Highways Agency's Design Manual for Roads and Bridges (DMRB) HD 24/06 where the expected design traffic is defined as the commercial vehicle loading over the design period expressed as the number of equivalent standard (80kN) axles (Highways Agency, 2006a). It is related to the commercial vehicle flow, design period, traffic growth, lane distribution, channelisation of traffic and wear factors as stated in ICE design guidance (Walsh et al., 2011b).

The factors used to convert commercial vehicle types into standard axles are known as wear factors. These are specified in Highways Agency (2006a) and are derived from the fourth power law, where the damaging effect is proportional to the fourth power of the load exerted by a vehicle's wheel onto the pavement surface. However, it should be noted that other studies have suggested a value larger than seven could be applicable depending on the pavement type, expected traffic and mode of deterioration (A. R. Dawson, 2008; Dormon & Metcalf, 1965; Jameson, 1996; Nunn, Brown, Weston, & Nicholls, 1997).

Theoretical structural design varies depending on wheel load distribution as well. When loads are distributed evenly, the pavement experiences less than theoretical wear. Under increased traffic loading, variation between vehicle wheels increases the overall average wear experienced by the pavement. Globally, studies and design codes have highlighted that load repetitions by heavy vehicles, results in considerable deterioration (Collop, 2002; Erlingsson et al., 2012). Despite there being a large body of evidence as to the damaging effect of different vehicle types on pavements, there is less evidence and guidance about the impacts of the distribution of traffic loads over the cross-section of the pavement. There is even less research on how the cross-sectional distribution of loading should be predicted for a new road in the UK. There is little empirical research relating to this, highlighting the relevance of this study.

2.4.2. Vehicle Lateral Displacement

Pavement performance depends on traffic loading configuration, and wheel paths. Wheel paths are directly related to the lateral positioning of travelling vehicles. It is defined as the perpendicular distance from the left front tyre of the vehicle to the edge of the pavement or lane which is shown in Figure 2.6 (Das, Jayashree, & Rahul, 2016). The edge of the pavement is usually taken to be the kerb line or road marking since it is the only available fixed feature on the road with well-defined edges (Ågren, 2003). Ideally, lateral distribution of vehicles in a lane would be uniform, wearing all parts of the pavement equally. However, a non-uniform pattern exists in the real world mainly depending on the size and speed of vehicles as well as the geometric design of roads, overall road condition, and traffic characteristics (Lee, Shankar, & Izadmehr, 1983).

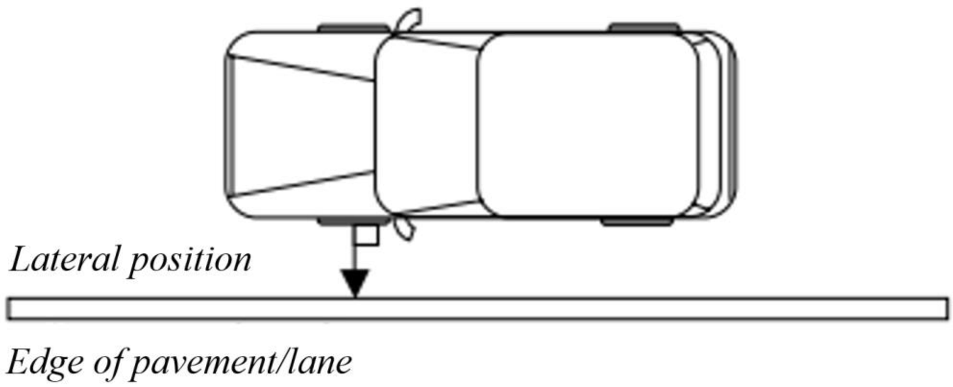


Figure 2. 6 Diagram of vehicle lateral displacement (Ågren, 2003)

2.4.3. Channelisation/Lateral Wander

The spread in the position of vehicles across a pavement surface is referred to as 'lateral wander'. In instances where there is very little lateral wander, the traffic can be referred to as 'channelised'. In channelised traffic, successive vehicles follow the same wheel path over a narrower section of the pavement surface. Channelised traffic might be expected at narrow sections of pavement such as traffic calming gateways, bus stops or car parks (Walsh et al., 2011b). Channelised traffic is usually considered to have a more detrimental impact on the pavement than traffic with a high degree of a lateral wander (Walsh et al., 2011b). Some design guides account for the effects of channelisation by increasing the traffic loading predicted to be carried by the pavement over its lifespan (Garrett, 1983; Walsh et al., 2011b). Pavements can then be designed with stronger materials or thicker layers to avoid premature deterioration. Such deterioration could include surface cracking, loss of texture, and in the case of flexible pavements, severe rutting, as can be seen in Figure 2.7.

Figure 2. 7 Rutting and polishing on pavements in Portsmouth

2.4.3.1. Geometric characteristics and lateral wander of traffic loading

To date, several studies have investigated the lateral distribution of traffic on pavements. Some have found associations between lateral wander and road width (Pauls, 1925; Taragin, 1945), and others with lane width (Buiter et al., 1989; Case, Hulbert, Mount, & Brenner, 1953; Erlingsson et al., 2012; Miller & Steuart, 1982). Pavements with wider sections tend to have a relatively larger spread of traffic while narrow sections can have highly channelised traffic patterns. Other studies found the lateral distribution of vehicle positions related to other characteristics of the road, such as horizontal curvature and their visual impression, gradients, shoulder widths, roundabout circles, and kerb heights (Case et al., 1953; Gunay & Woodward, 2007; Pauls, 1925; Summala, Merisalo, & Vierimaa, 1978; Taragin, 1944; J. van der Walt, Scheepbouwer, & West, 2017; Weise, Steyer, Sossoimihen, & Roeder, 1997), and also based on vehicle type and composition (Miller & Steuart, 1982; Taragin, 1944). Additionally, edge line-markings and their width appeared to be related to the lateral spread of cars causing drivers to travel towards to the centreline of the road (Nedas, Balcar, & Macy, 1982; Van Driel, Davidse, & van

Maarseveen, 2004). A relationship with vehicle speed has also been suggested with speed influencing vehicle position and vice versa (Blab & Litzka, 1995; Hallmark, Hawkins, & Smadi, 2013; Summala et al., 1978).

Finally, rutting has been found to be associated with channelised traffic (Blab & Litzka, 1995; Erlingsson et al., 2012). It is unclear as to the causality, but it is suggested that there is a feedback loop with channelisation causing rutting, which then further exacerbates the channelisation and so on (Aydin & Topal, 2016; Blab & Litzka, 1995).

2.4.3.2. Channelisation in pavement design guidance

The first study to consider channelisation as a factor in the calculations of design traffic in the UK was conducted by Kent County Council in 1983 and suggested applying a factor of 2 to the total traffic load to represent a doubling of the damaging effect of the traffic loading that might be expected under channelised (referred to as canalised in the paper) conditions (Garrett, 1983). The rationale for the factor of two appears to be based on a theoretical consideration of a normal distribution of vehicle positions on a wide lane and narrow lane, as shown in Figure 2.8. However, what would constitute a wide or narrow lane is not defined. While the UK design standards (Highways Agency, 2006b), do not consider channelisation effects, several widely used supplementary design guides do. The ICE manual (Walsh et al., 2011b) suggests that when channelised traffic is expected, the traffic loading is doubled. The rationale for this advice relates to the theoretical work undertaken by Kent County Council (Garrett, 1983). However, little is said in the design guides as to when such channelisation might occur. This design guidance and the underpinning theory do not consider degrees of channelisation, but instead suggest only a binary measure (channelised or un-channelised).

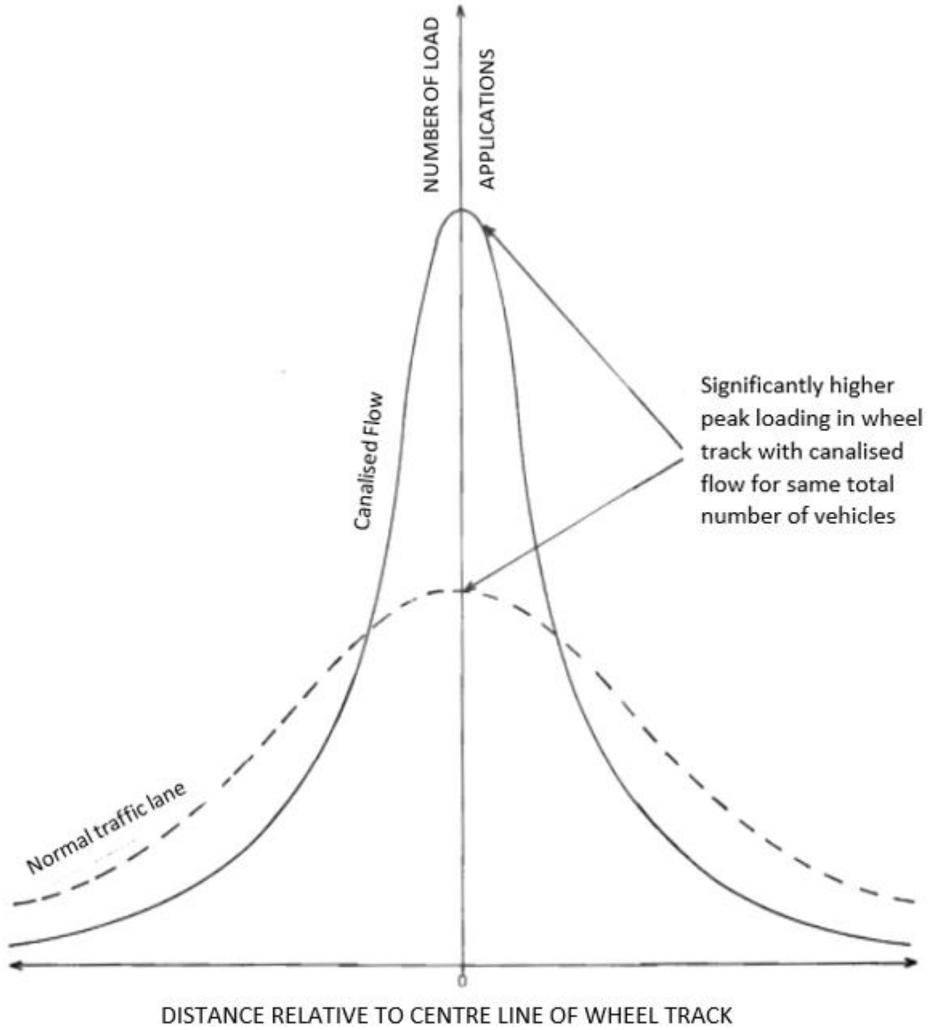


Figure 2. 8 Effect of canalised traffic flow on peak damaging power (Garrett, 1983)

In other national design guides, the distribution of traffic loading across the pavement is considered on a scale, based on the width of the lane. For instance, according to the German Road Design Manual, channelisation is considered on a scale based on lane widths from 2.50 metres where full channelisation is expected to 3.75 metres where no channelisation is expected (Sieber, 2012).

Similarly, Austrian design guidance, informed by a study conducted by Blab and Litzka (1995) considers lane width, measured on a scale, to be the only factor that determines the lateral wander of vehicles.

Likewise, in the Netherlands, the lane width is considered to have a linear relationship with the damage caused by the traffic due to the effect on the distribution of the loads (Atkinson et al., 2006; Buiter et al., 1989).

Based on consideration of international design standards and the limited research underpinning them, it seems plausible that the degree of vehicle wander ought not to be a binary judgement as is the case in the UK design guidance. Those geometric characteristics that might affect the degree of wander in the UK and whether these differ from international design guides is currently unknown.

2.4.3.3. Channelisation of traffic and flexible pavement performance

The exact behaviour of flexible pavements under repeated wheel loads is difficult to predict due to the different properties of materials, the nature of loadings and their failure modes (Huhtala, 1995).

There are a limited number of studies that have shown that the widths of roads and traffic lanes are related to the degree of channelisation, with wider roads and lanes having lower levels of channelisation and vice versa (Atkinson et al., 2006; Blab & Litzka, 1995; Erlingsson et al., 2012; Sinanmis & Woods, 2019). As a result of channelisation, some studies indicate that road pavements deteriorate more rapidly when there is less/limited freedom for the wandering of wheel loads (Blab & Litzka, 1995; Erlingsson et al., 2012). Rutting is a common deterioration (deformation) mode of flexible pavement structures due to repeated load applications along the wheel paths (Blab & Litzka, 1995; Brito, 2011; Erlingsson et al., 2012; Harvey, Roesler, Coetzee, & Monismith, 2000; Kasahara, 1982; Pais, Amorim, & Minhoto, 2013; Shafiee, Nassiri, Eng, & Bayat, 2014; J. D. van der Walt, Scheepbouwer, Pidwerbesky, & Guo, 2017). Figure 2.9 and Figure 2.10 illustrates the development of rut depth with load applications regarding some of the conducted studies.

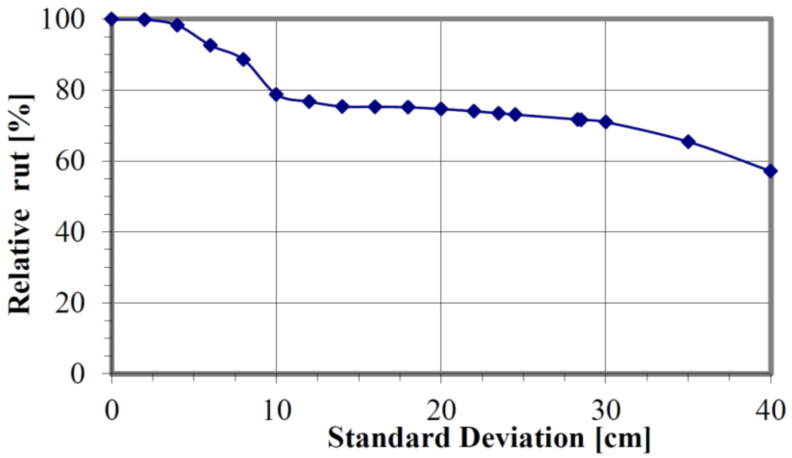


Figure 2. 9 Relative surface rut as a function of the standard deviation of the lateral wander (Erlingsson et al., 2012)

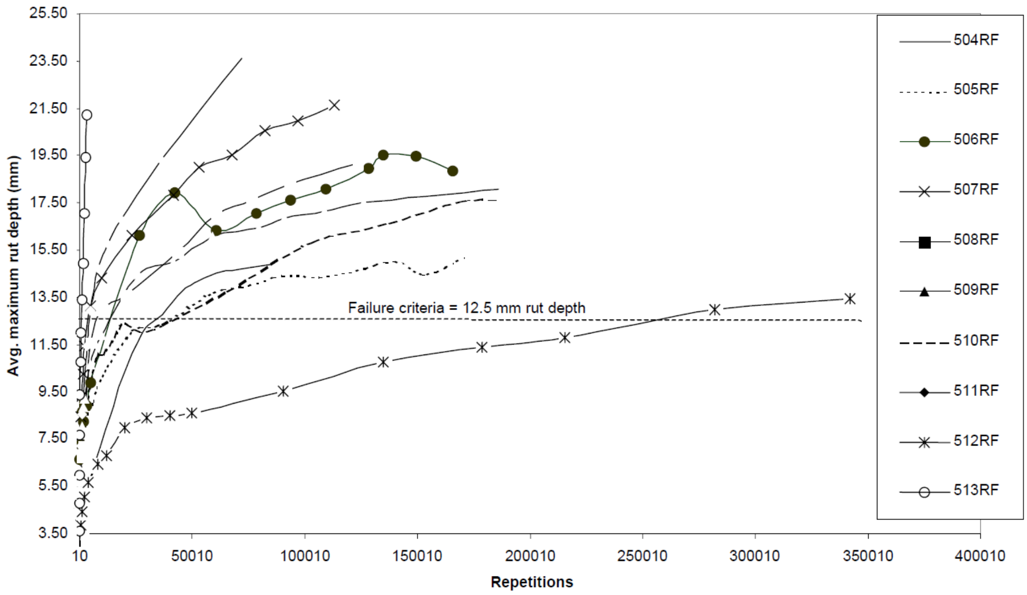


Figure 2. 10 Plot of average maximum rut depth versus load repetitions for all test sections (Harvey et al., 2000)

In Figure 2.9, it can be seen that standard deviation influences rutting development. Figure 2.10 also demonstrates that the rutting accumulates with the number of load repetitions.

Tests were also undertaken of the performance of pavement sections using Heavy Vehicle Simulations (HVS) in South Africa and by the California Department of Transport (Rust, Harvey, Verhaeghe, Nokes, & van Kirk, 1994). One of the objectives of these research projects was to evaluate pavement rutting from channelised traffic through a laterally guided Automated Vehicle Control Systems (AVCS), without wander, and without lateral and longitudinal forces associated with acceleration and braking (Harvey et al., 2000). The repetitive use of a single precise wheel path (absence of wheel wander) resulted in an increased rate of rut depth between 25% and 45%. Temperature also had a significant effect, accelerating rutting behaviour when hotter (Rust et al., 1994). These test conditions demonstrated only perfectly channelised or perfectly distributed traffic, giving little in the way of guidance as to how real traffic distributions (unlikely to be either perfectly channelised or perfectly distributed) affect rutting. The progression of maximum rut on the two sections are shown in Figure 2.11. However, it should be noted that this relates to theoretical distributions of vehicle positions, one pavement type, the same load applied and sample size is small.

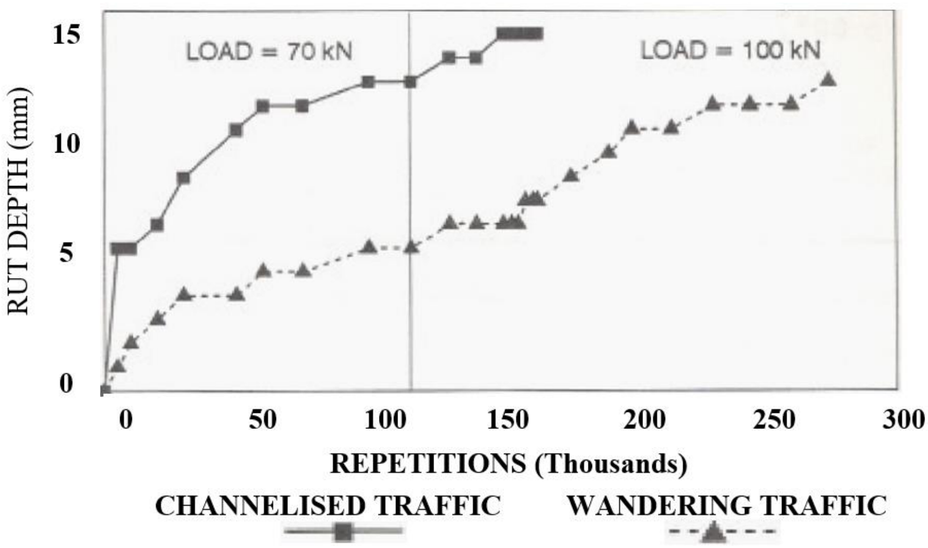


Figure 2. 11 Progress of rutting on the channelised and wandering traffic sections (Rust et al., 1994)

To prevent premature deterioration, some researches (Blab & Litzka, 1995; Buiter et al., 1989) suggest that the thickness of pavement can be increased when channelisation is expected. Blab and Litzka (1995) in Austria and Buiter et al. (1989) in the Netherlands expressed the lateral wander of wheel positions through a shift factor which is then applied to pavement thicknesses.

Finally, there are questions as to the causality in the relationship between channelisation and rutting. It is suggested that there is a feedback loop with channelisation causing rutting, which then further exacerbates the channelisation, and so on (Aydin & Topal, 2016).

Based on consideration of international design standards and in the case of the UK, the very limited research underpinning them, the importance of channelisation of traffic for pavement design and analysis is somewhat unclear. There is little in the way of guidance in the UK as to when traffic might be expected to be channelised, and the doubling of the traffic load when this is expected is based on little empirical evidence. Therefore, this study aims to give further guidance as to the damaging effect of rutting on flexible pavements in the UK.

2.5. Pavement Management System (PMS)

A pavement management system is a decision support tool, aggregating several data sets to assist managers in providing, evaluating and maintaining pavements to a serviceable condition (AASHTO, 2012). Highway agencies that have incorporated pavement management principles into their operational practice were agreed that they can deliver real benefits in the form of financial and economic savings resulting from more appropriate and more timely maintenance treatments (Spong, 2005).

Pavement management systems are used to support agency decisions at two levels in the UK (Thom, 2015). At the network level, summary information related to network budget requirements and consequences enables the allocation of funds according to priorities and the scheduling of maintenance actions (Van Wijk & Sadzik, 1998). The required information from the pavement management at the project level is an estimate regarding preferred maintenance actions for each project in terms of the cost and the expected life cycle (Van Wijk & Sadzik, 1998).

2.6. Pavement Management Components and Benefits

A pavement management system supports different tasks. These include pavement condition monitoring; a database containing all related pavement information, analyses, decision criteria and implementation procedures. The parameters are used to achieve a targeted performance level, identifying the most practical combination of maintenance activities under planned funding or predict future conditions under different investment strategies (Zimmerman, 2017). Monitoring of the maintenance is also fed back into the system.

AASHTO (2012) summaries a variety of different benefits of using a PMS, including but not limited to:

- The effective and critical use of available resources to improve pavement performance.
- The ability to justify related funding needs.
- A clear understanding of current and future pavement condition and needs.
- Improved access to pavement information throughout the agencies.
- Increased critical thinking in the decision process.
- Objective decision making based on data.

2.7. Pavement management information and condition data

Information is central to the management of a pavement asset (Costello & Snaith, 2015). Such information is typically referred to as inventory data and condition data. Inventory data is used during the processing of condition data that will affect the way how it was processed by providing information on the area of the highway pavement in which a deterioration has been recorded (Wallis, 2009). A pavement starts to deteriorate as soon as it is constructed and opened to traffic. For example, the coefficient of friction on the surface reduces over time, longitudinal depressions develop in wheel paths, cracks develop in the pavement structure, and the riding quality of the surface decreases (Costello & Snaith, 2015). Hence, all the information data that affect pavement condition should be gathered.

The asset manager needs to establish what services they want to provide based on the investment required to maintain the assets (Thorp, 2011). Therefore, condition data is an essential step towards to modelling of pavement performance. Typical condition data that are collected include information on the structural and functional performance of the pavement, as follows (Costello & Snaith, 2015):

- Surface deflection: This is a measure of the deflection of the surface of the pavement evaluations for the load transferring pavement structure. The magnitude and shape of pavement deflection is a function of traffic (type and volume), pavement’s structural section, temperature and moisture affecting the pavement structure. It is usually measured using the falling weight deflectometer (FWD).
- Roughness: It is a measure of the longitudinal deviation of the pavement profile. A laser profilometer attached to a Traffic-Speed Condition Survey (TRACS) vehicle is commonly used for measuring the international roughness index (IRI) as an indicator of ride quality.
- Surface texture: It is a measure of the texture of the road surfaces and typically measured in the wheel tracks using a high-frequency laser attached to a Traffic-Speed Condition Survey (TRACS) vehicle.
- Skid resistance: This is a measure of the in-service friction of the pavement surface. The level of skid resistance is usually measured using the sideway-force coefficient routine investigation machine (SCRIM).

- Wheel track rutting: Longitudinal depressions formed under the wheel due to heavy loading. It is typically measured in the UK using the surface condition assessment for the national network of roads (SCANNER).
- Cracking: This is investigated as longitudinal, transverse, block or crocodile cracks on pavement surfaces. Although traditionally recorded using visual surveys, it can also be captured by SCANNER survey.
- Surface defects: Various other surface deteriorations such as potholes, ravelling, or fretting and flushing. They can be recorded visually as well as Traffic-Speed Condition Surveys (TRACS).

Usage and environmental data are often also included (Costello & Snaith, 2015):

- Measures of rainfall and temperature from weather stations.
- Annual average daily traffic (AADT).
- Heavy commercial vehicle (HVC) flows.
- Equivalent standard axle load (ESAL).

2.8. Pavement Deterioration Model Requirements

After collecting the data, it can be then used to provide critical parameters for deterioration paths to calculate precise deterioration models for the highway network (Thorp, 2011). Models can be developed to address pavements that are suffering rapid deterioration, and these can be addressed in advance by calculating the rate of deterioration as a function of the pavement structure, age, traffic loads and environmental variables.

Recent investigations have addressed some issues of the deterioration model and recommendations for future pavement management systems. These are related to the performance models for pavement behaviours that need to be developed in order to determine the deterioration mechanism and incorporate related maintenance and rehabilitation activities. Specifically it is suggested to integrate deterioration models that consider uncertainty, such as future cost of maintenance, traffic volumes, and available sources, while incorporating the sources of economic and environmental parameters that explain the heterogeneous nature of pavements (Swei, Gregory, & Kirchain, 2015). Specifically, the use of traffic loading information is used in PMSs to assist in the identification and prioritisation of required maintenance and rehabilitation measures, in the calculation of vehicle operating costs (VOC) for use in the quantification of benefits and pavement prediction models and related optimisation procedures (Van Wijk & Sadzik, 1998). Within the scope of this research, the influence and contribution of traffic loading (channelisation issue of traffic loading) in PMSs will be studied and essential suggestions aimed to provide in the successful implementation of a PMS in the UK.

2.9. Pavement maintenance treatments

Under the influence of both traffic loading and environment, the level of overall deterioration reaches a point where the performance of the pavement is endangered. At this point, pavement needs intervention to upgrade its performance to an acceptable level. In practice, there is no definitive set of intervention levels it may differ from one instance to another. However, studies have shown that some condition parameters can experience an accelerated progression stage that represents a rapid failure of pavement towards the end of its design life (Henning, Costello, & Watson, 2006). Figure 2.12 represents pre-determined triggers for an evaluation of optimum time for intervention versus the overall condition of the pavement.

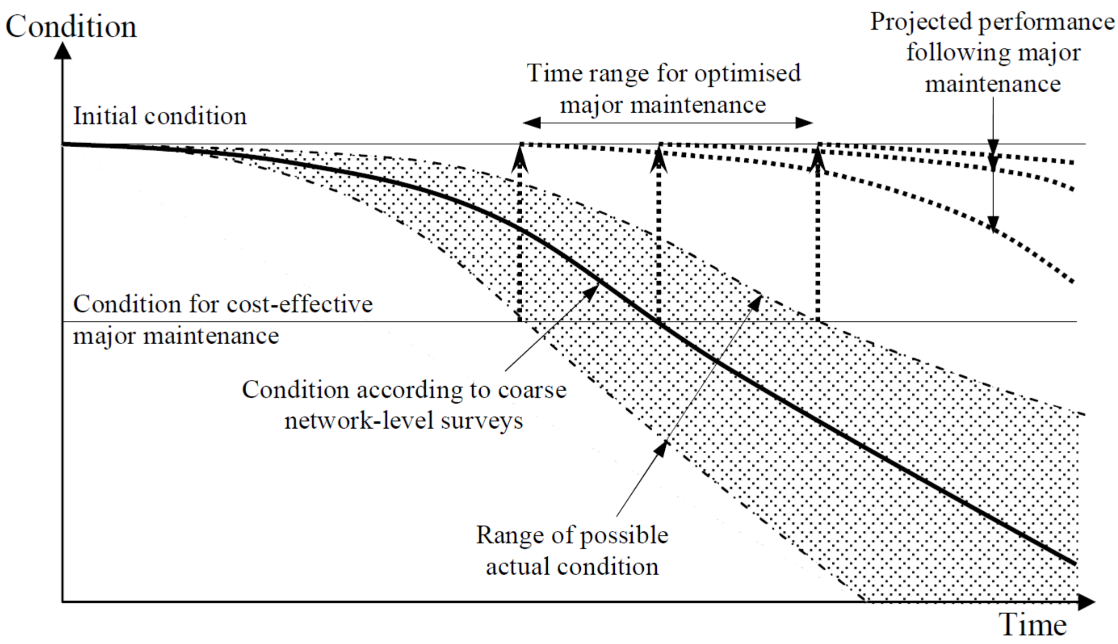


Figure 2. 12 Illustration of intervention levels based on overall condition (Thom, 2015)

2.10. Chapter Summary

This chapter outlined the types of pavements, categories of deterioration modes and the damaging effects of traffic in detail. Particularly the impact of channelisation and how this is influenced by various parameters along the pavement. From the reviewed literature, it can be seen that there is little evidence that exists in terms of categorising traffic flow as either channelised or not when designing a pavement in the UK. However, when traffic is considered to be channelised a factor of ‘2’ is applied, which stems from theoretical considerations of the distribution of wheel positions. Design guides in other countries suggest the use of ‘lane width’ as a proxy for vehicle wander/channelisation instead. However, the empirical evidence supporting these models is limited. Moreover, as pavement designs, materials, maximum vehicle loading, weather conditions, soil conditions, maintenance regimes, road markings, traffic laws and vehicle types differ considerably between countries, the results of studies in one context cannot be assumed to hold in other contexts.

Furthermore, the reviewed studies tend to be based on either theoretical models or laboratory experiments. Field observations are likely to give a better representation of actual driving behaviours, and none have been found that were undertaken in the UK. Therefore, this study aims to address this gap in knowledge and provide guidance to practitioners in the UK and overseas on the factors that might influence vehicle wander. It also gives further guidance as to the damaging effect of channelisation/lack of vehicle wander on flexible pavements in the UK.

Pavement management systems are then reviewed as tools for decision making roles in maintenance. Since the influence of traffic loading on the remaining life of a pavement determines deterioration modelling; accurate prediction of the effect of channelisation is required for detailed pavement analysis and management.

Chapter 3 Research Design and Methodology

3.1. Introduction

This chapter outlines the proposed methodology, and defines the research design and scope of the study.

3.2. Research Scope

The aim of the research is to shed light on the effect road geometries and features have on pavement deterioration through their influence on the channelisation of traffic.

For the purposes of this study, it was decided to concentrate on flexible pavements only, which are the most common pavement type in the UK. Flexible pavements may be more prone to the effects of channelised traffic than rigid pavements due to their viscoelastic properties. Also, it was decided to focus on rutting as the deterioration mode. Rutting is a common deterioration mode on flexible pavements and can be easily measured on a scale. Research suggests that rutting and channelisation of traffic could be closely associated with each other. Finally, the scope of the research extends only to case study pavement sections in the City of Portsmouth UK.

In order to pursue the objectives, the next section explains the research design in terms of strategies and methods of data collection and analysis.

3.3. Research Design

The research philosophy refers to systems of beliefs and assumptions about the development of knowledge (Saunders, Lewis, & Thornhill, 2009). The assumptions that underpin the research philosophy shapes all aspects of the research. The epistemological and ontological positions in this research are based on the nature of the truth and proof in modelling channelisation and pavement condition. The position adopted in this research is positivist, hence pavement performance is measured and quantified. Specifically, the adopted the methodological choice of this research is purely quantitative. Furthermore, the data collection technique adopted is observational. Observations depend on the direct presence of the researcher in the field and recording the status of the object under consideration; an observation does not depend on opinions or perceptions of other people (Denscombe, 2014). In addition, Collis and Hussey (2009) agree that observation is suitable for both positivist and phenomenological methodologies. Other researchers have preferred observations to experiments such as Blab and Litzka (1995) and Buiter et al. (1989). The benefit of adopting an observational method in this research is that actual driving behaviours, road geometries and features and deteriorations can be analysed, as opposed to fictitious scenarios used in the laboratory and theoretical work reviewed in Chapter 2.

3.4. Case study location

Data were collected through observations in the City of Portsmouth, UK, due to availability of data and a consistent climate, as shown in Figure 3.1.

Portsmouth is an island port city located on the south coast of England with a population of around 200 000 (Hampshire County Council, 2018). It is the most densely populated city in the UK outside of London (Finch, Brangier, & Chaignon, 2008).

Portsmouth International Port, formerly known as the commercial or continental ferry port, is used to import and export goods that brings heavy wheel loads applied to pavements in and around the city. The city suffers from the congestion typical to most UK cities (Cotterill, 2017). The high population density, concentration of significant industries and significant through traffic to the Isle of Weight and Europe with limited use of public transport results in heavy traffic loads across the city.

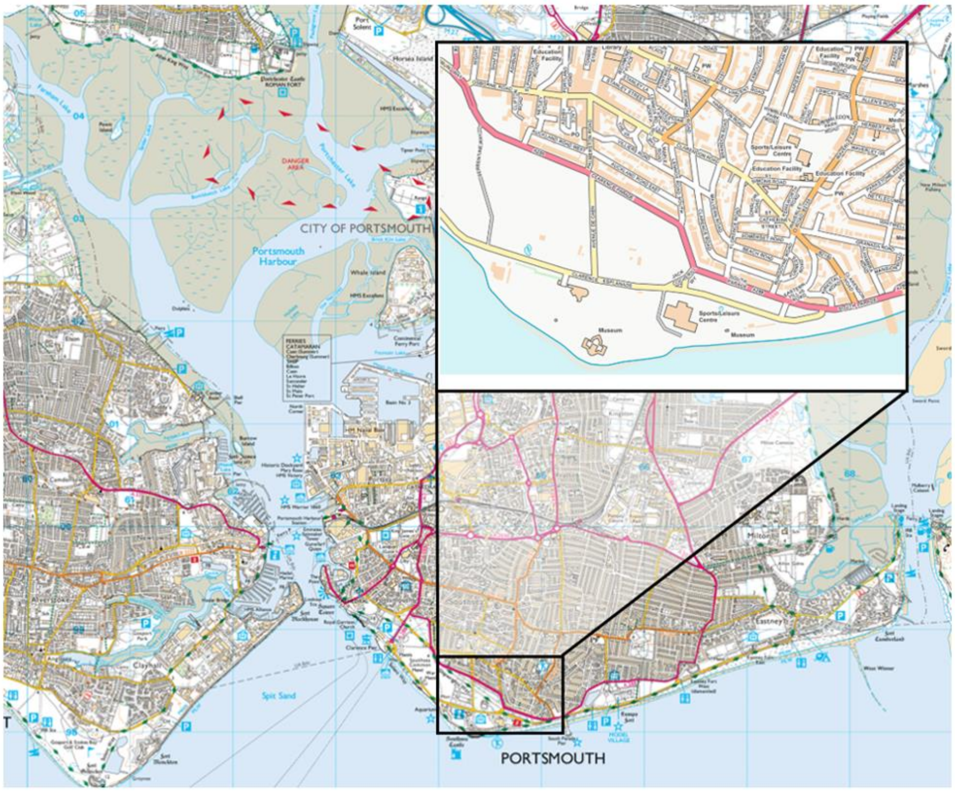


Figure 3. 1 Location of study area – Clearance Parade and South Parade (Ordanance Survey, 2019)

Two primary roads, the A288 Clearance Parade/South Parade (stretching approximately 1530 m) (Figure 3.1) were selected because traffic flow/composition is similar along their lengths and there is no significant change in longitudinal road gradient. There was also minimal variation in climatic conditions along its length, while the geometry (width of lane and road, curvature and camber) and presence of road features varied considerably. No recent maintenance had taken place except minor treatments such as improving the skid resistance and sealing cracks.

The pavement type was flexible pavement, which had homogenous characteristics in terms of the structure along its length (Heavy Duty Macadam with 0/200mm aggregate and 50 penetration binder). Core sample data provıded by COLAS Ltd. and a visual inspection of the selected road sections indicated that the pavement was homogenous along its length as seen Figure 3.2 and Figure 3.3. It is also important to note that this pavement structure was selected for research because it is one of the most commonly utilised pavement structures for highways in England (Pell, 1978).

I would change this to say, "Core sample data provided by COLAs Ltd and a visual inspection of the selected road sections indicated that the pavement was homogenous along its length as seen in...."

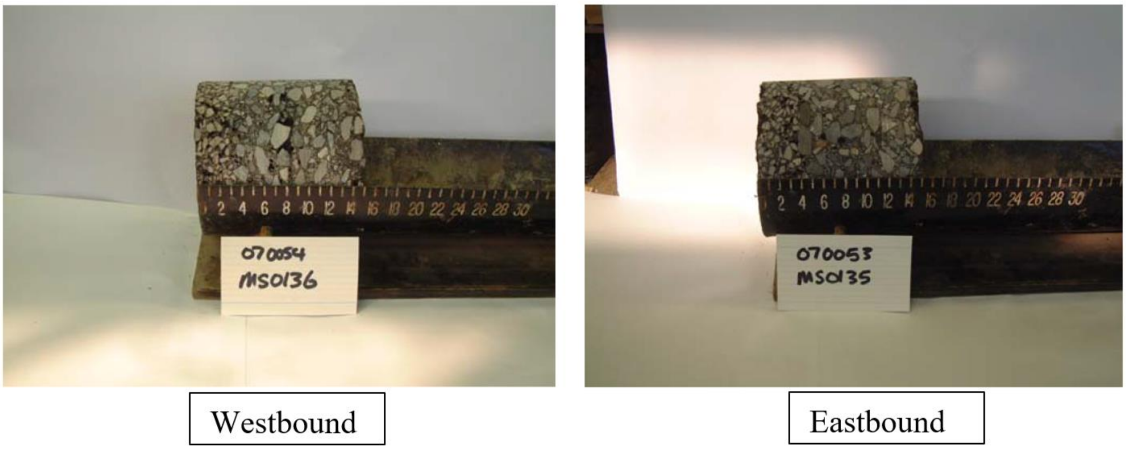


Figure 3. 2 Core sample of Clearance Parade (Supplied by COLAS Ltd.)

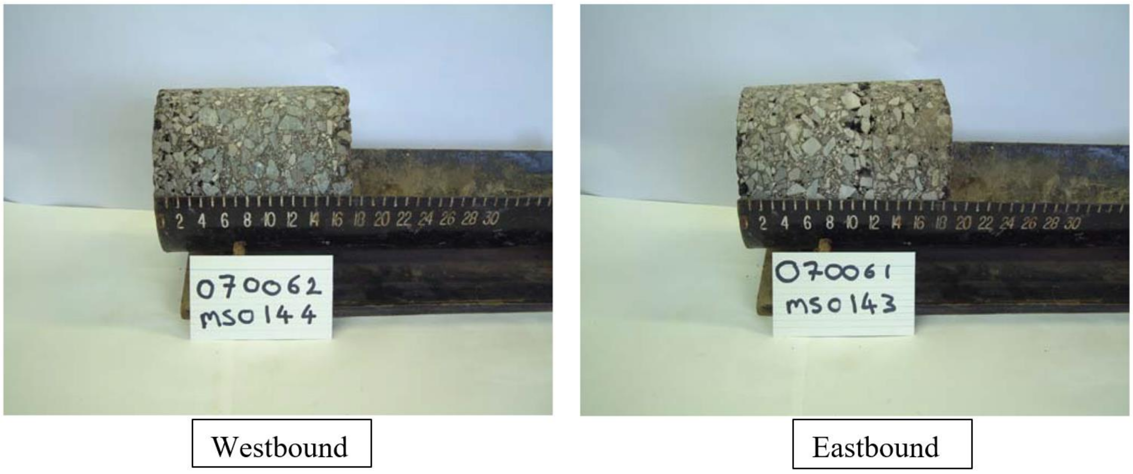


Figure 3. 3 Core sample of South Parade (Supplied by COLAS Ltd.)

The soil condition data was checked from Geological Map data using Digimap and it appears that the soil conditions were uniform along the length of the selected road sections as shown in Figure 3.4.

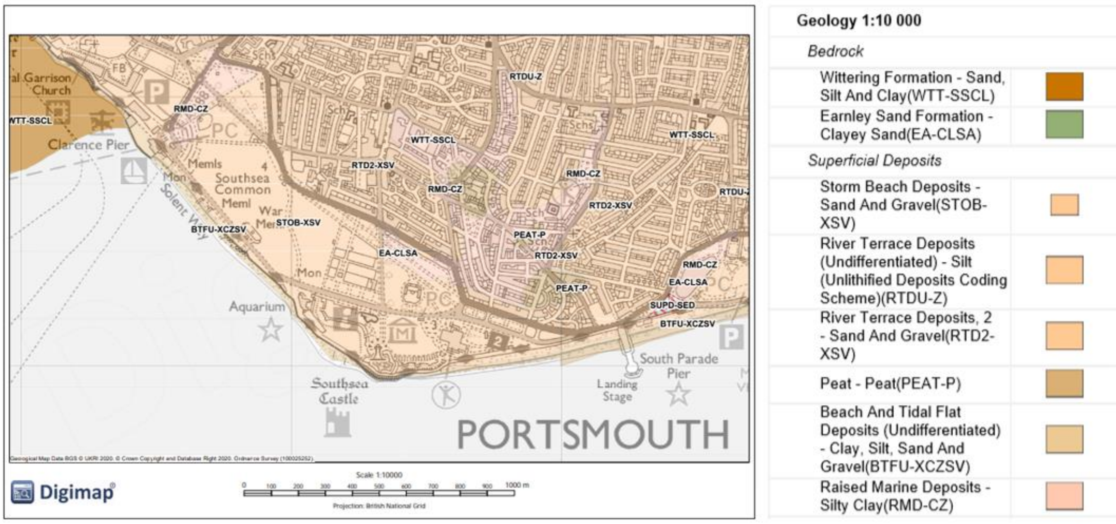


Figure 3. 4 Geological map data – Soil types (Digimap, 2020)

3.5. Data collection method

The research involved both primary and secondary data. As the name suggests, primary data is collected for the first time by the researcher, while secondary data is collected or produced by others (Ajayi, 2017).

The secondary data was obtained from Portsmouth City Council and its Highways contractor COLAS Ltd through their regular surveys for road condition. COLAS operate a 25 year Private Finance Initiative (PFI) highway maintenance programme on behalf of Portsmouth City Council (Finch et al., 2008). This requires regular collection of pavement condition data which were provided for use in this study. This included SCANNER survey (Surface Condition Assessment for the National Network of Roads) data (Department for Transport, 2009). The SCANNER data were collected for different traffic lanes and directions for different years. The data for road conditions obtained from COLAS includes rut depths in millimetres for nearside (left) wheel paths and offside (right) averaged over 10 m lengths. Camber (% cross fall) and horizontal curvature (radius of curve) were also collected from COLAS as explanatory factors. All the data supplied by COLAS were taken from three different survey years.

The primary data were collected by measuring the lateral placement of vehicles under investigation. Most recently used measurement methods in the literature can be grouped into three categories: manual observation, precision camera, and sensor based devices (Luo & Wang, 2013).

3.5.1. Manual observation

Manual observation is the oldest technique by using a reference line placed on the road section to measure the distance between the right front wheel of the vehicles and the reference line by the observer. This was applied by Taragin (1945), Pauls (1925) and Gungor (2018). However, this method has fallen out of favour due to it being laborious, and accuracy and subjectivity concerns (Summala & Merisalo, 1978).

3.5.2. Precision camera

The use of a precision camera is the most commonly used method which involves processing the videos that are collected by cameras (Gungor, 2018; Luo & Wang, 2013). The camera can be installed on either the vehicle or on highway infrastructure (e.g. bridge or footway).

Shankar and Lee (1985) used a video camera mounted in a following vehicle to record the distance between the right edge of truck tyres and the left side of the pavement in the United States (US). Also, Triggs (1997) recorded the lateral position of vehicles with a camera mounted unobtrusively an the experimental vehicle travelling along a 20 km straight road. Similarly, Lennie and Bunker (2003) used a video camera attached to the centre of the roof of the vehicle to measure the lateral displacement of vehicles.

Benekohal, Hall, and Miller (1990) obtained lateral distribution data by mounting the camera on bridges over the highway. Lennie and Bunker (2005) later conducted a study by placing the camera on the pedestrian walkway over the pavement section of interest. In Istanbul, Gunay (2004) used a camcorder with a small tripod placed on roadway bridge passing over the carriageway, as part of the first study into lane utilisation on Turkish highways. Other research carried out by Stempihar, Williams, and Drummer (2005), Gunay and Woodward (2007) and Aydin and Topal (2016) used a similar process in the United States, and Northern Ireland and Izmir, Turkey, respectively.

There are several techniques, which are used for measuring the related distances from video footage. Gunay (2003) introduced these techniques:

1. “Picture superimposition; this is a method where the road is required to be closed to traffic in order to place a large “ruler” across the carriageway and a photograph of the road without traffic is taken. The ruler is then removed, the road is opened to traffic and the flow of traffic is recorded. The picture of the empty road with the ruler on and the video record of the traffic are then superimposed for the analysis. Case et al. (1953) used this method by placing a marker board across the highway. However, this method requires interruption into the traffic flow, therefore, it may not be preferred.
2. Screen/Scale superimposition; this method is similar to the previous method except no reference board is required and therefore no traffic interruption. After recording the traffic flow, the screen superimposition uses an appropriate screen ruler, which is applied on the screen to establish the measurements. The scale superimposition also uses a screen ruler but this time, for reading the number of pixels from one point to another. This is then scaled to real world dimensions. Both methods involve cost effective installation of equipment, nevertheless, the analysis may be time consuming.”

Miller and Steuart (1982) used this method by filming the sites and then analysed these with a time-lapse photographic technique.

Shankar and Lee (1985) used this method in Texas on a computer screen. Measurement of lateral distances were recorded from replayed images on a video monitor with the aid of a grid placed on the curved screen. The grid sizes were scaled based on the lane width. Triggs (1997) used a similar methodology on the screen by using lane width as a measurement reference, enabling the distance measured on the screen to be converted to the actual lateral displacement in Australia.

Lennie and Bunker (2003) used the same method by extracting the lateral position of vehicles from the videos. An on-board computer was used to record the distance on the video screen. A second camera was mounted on the prime mover to observe the front right wheel and the pavement beneath it. This image was displayed on the screen beneath the image displaying the overhead view to the tracking ability boards, so that they could be recorded and later viewed simultaneously. The experimental vehicle is illustrated in Figure 3.4.

Figure 3. 5 Output from video recordings (Lennie & Bunker, 2003)

Lennie and Bunker (2005) and Bunker and Parajuli (2006) in Australia adopted a similar method for measuring the position of vehicles from a pedestrian walkway of an overpass over a section of selected motorway. The video footage was recorded and analysed digitally using a program that allows frame-by-frame analysis. Pictures from the fieldwork and analysis can be seen in Figure 3.5 and Figure 3.6.

Figure 3. 6 Screen-shots of lateral positions of vehicles (Lennie & Bunker, 2005)

Figure 3. 7 Camera mounted on the overpass (Bunker & Parajuli, 2006)

Stempihar, Williams, and Drummer (2005) and Luo and Wang (2013) analysed the data by painting reference lines on the pavement before the test and the lateral placement of vehicles were identified in relation to the marking lines as shown in Figure 3.7 and Figure 3.8.

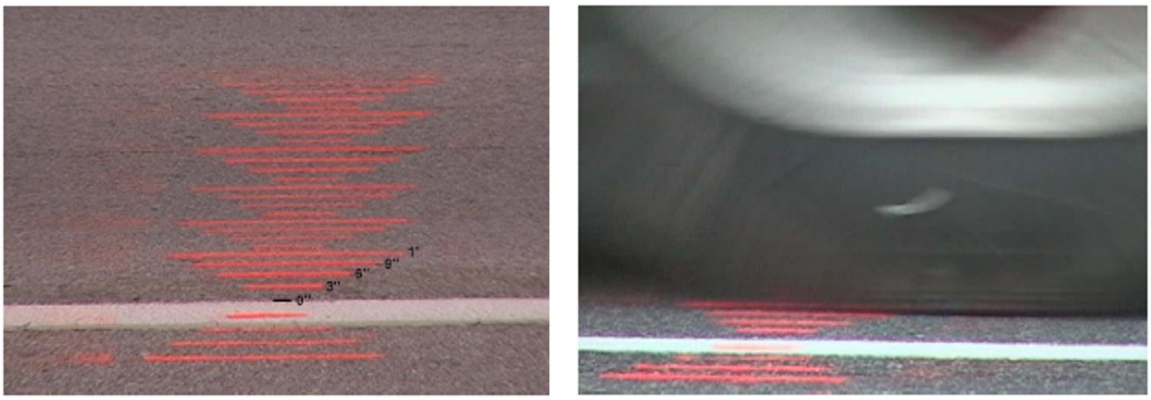


Figure 3. 8 Painted reference lines and tire passing example (Stempihar et al., 2005)

Figure 3. 9 Marked reference lines and measurement of lateral distance (Luo & Wang, 2013)

Gunay and Woodward (2007) and Aydin and Topal (2016) followed the same method while analysing the data. They both used screen ruler software, called MB-Ruler, to measure the distances on the screen. Gunay and Woodward (2007) measured the distances in terms of the number of pixels as shown in Figure 3.9. The distances were then converted to real-world dimensions.

Whereas, Aydin and Topal (2016) first divided the road surfaces into 20 cm distances on the screen (as shown in Figure 3.10) and calculated the lateral position by using the following Equation (1):

$$T = \frac{\sum_{i=1}^{n} l_i}{N} \, . m_n \qquad \textit{Eq. 1}$$

where: T – position of right and left wheels of the vehicle on road surface [cm];

l_i – lane width [cm];

N – selected constant range distance for scaling purposes [cm];

m_n – beginning from the shoulder, the range where right or left wheel of vehicle takes place.

Figure 3. 10 Screen superimposition technique used in the data analysis (Gunay & Woodward, 2007)

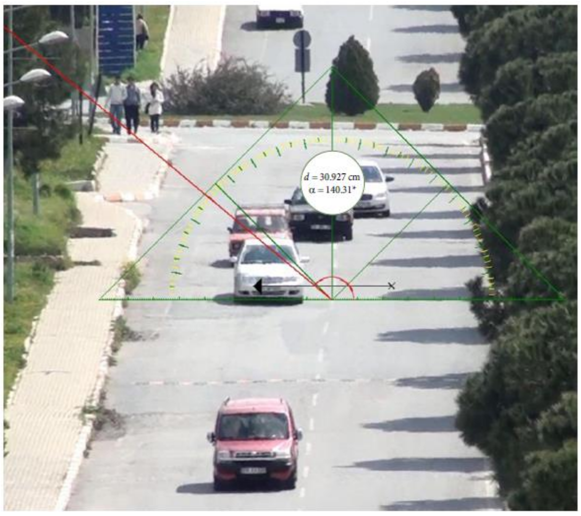


Figure 3. 11 Application of screen superimposition technique (Aydin & Topal, 2016)

Furthermore, Weise et al. (1997) conducted a study using a video processing technique by pixel analysing the recording with software called "Viva*traffic*" to determine the lateral placement of vehicles. Markings on the roadside surface were first placed to define a scale; later removed in order not to distract drivers' behaviours.

3. Light tracking; the use of this method is only available night-time driving which calculates positions from the locations of the lights of vehicles in the picture.

4. <u>Laser beams;</u> this method measures the lateral position of a number of vehicles in particular locations of road networks with fully-automated and portable equipment. It uses photocells which are set over the road at a known angle with respect to others. The approach is first utilised by Summala and Merisalo (1978), is automated with no traffic interruption, however, the equipment may not be easily available everywhere.

3.5.3. Sensor Based Devices

Sensor based devices contain detectors and are able to obtain data on the longitudinal characteristics as well as lateral characteristics of traffic (Gunay, 2003). The detectors can be placed as either instrumented mats on the surface or as embedded sensors in the road surface (Gungor, 2018).

Buiter et al. (1989), Nishizawa, Kajikawa, and Fukuda (1993), and Blab and Litzka (1995) used instrumented mats for measurement of the lateral shifts of the wheel paths on the road surface. The mat contained 120 switch elements, each 0.02 m wide. When a vehicle passed, these switches were activated and the information was registered by means of a microcomputer. The equipment is illustrated in Figure 3.11 and Figure 3.12.

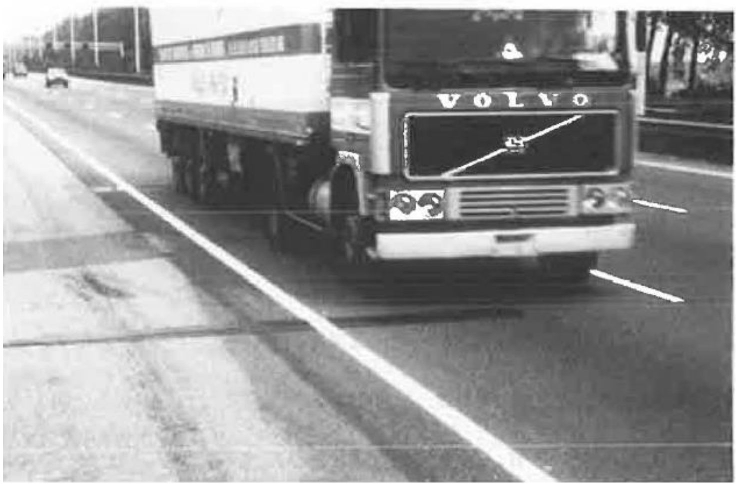


Figure 3. 12 Sensing mat for measuring lateral shifts of the wheel path (Buiter et al., 1989)

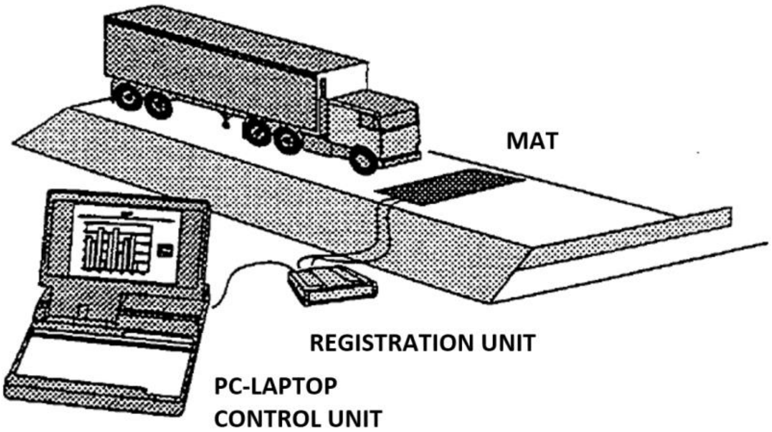
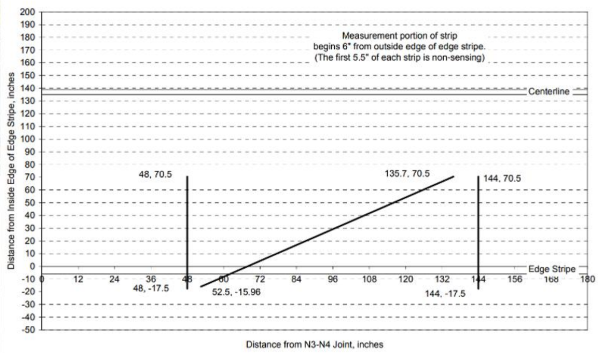


Figure 3. 13 Lateral displacement system (LDS) (Blab & Litzka, 1995)

Moreover, Timm and Priest (2005) embedded three axle sensing strips with a specific layout, “Z” form in road segments as shown in Figure 3.13a. The lateral distance of a wheel was then computed from the precise geometric layout of the sensor by using trigonometric relations as presented in Figure 3.13b.

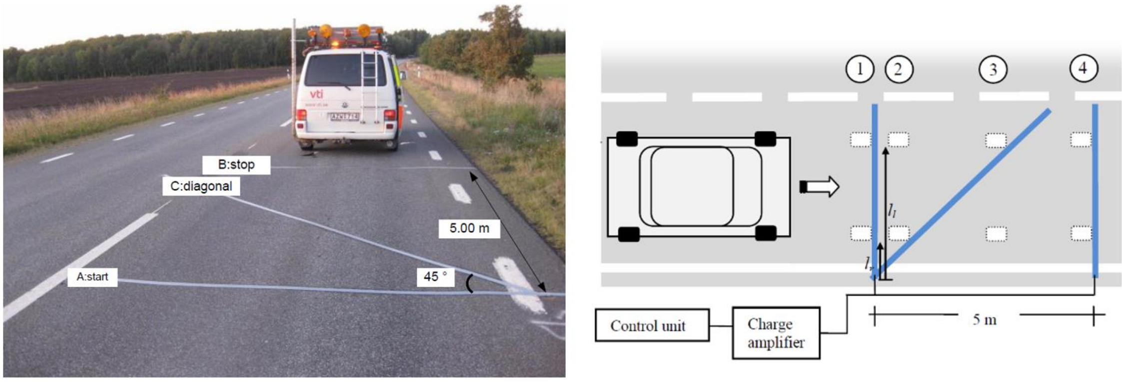
(a)Instrumentation strips



(b)Strip layout

Figure 3. 14 Sensor layout and instrumentation (Timm & Priest, 2005)

Erlingsson et al. (2012) developed a similar system in Sweden, where coaxial cables were glued in two vertical and one 45º angle diagonal (“Z” form), as presented in Figure 3.14. The time between a tyre hitting two of the cables were then used to determine the location of tyres for the lateral position of each vehicle.



(a)The system set up

(b)Measuring system

Figure 3. 15 Coaxial cable layout and instrumentation

In the application of the described methods above, there are some important issues related to economy, safety and precision of the method that need to be considered. The next section describes the method that was to be used in this study to determine the lateral position of vehicles.

3.5.4. Method designed for measuring the lateral position of vehicles

A novel observational method of data collection was designed for this study where real time traffic footage data was recorded using an advanced image processing camcorder with a durable tripod, presented in Figure 3.15. Simulation and laboratory experiments would not have been suitable as there would have been an influence over driver behaviour and would lack other extraneous variables, which were present during naturalistic observations. This method was chosen as it gives high external validity and realistic results providing a greater value to the research. In addition, following reasons were also considered:

- Availability: The camcorder and memory card for the traffic footage records are easy to be purchased and used. Analysis of traffic footage can also process by using basic drawing software.

- Ergonomic: Since the data was collected in Portsmouth City only, the camcorder and tripod had an advantage of being easy to change the location and to be installed and operated compared to the installation of two strips at multiple locations which would not have been possible.
- Safety: The interruption of the traffic flow was not required as the camcorder could be fixed a considerable distance away from the road edge out and drivers’ route in order not to influence their traffic pattern.
- Economic: The camcorder is more cost effective to purchase and install than other types of sensor devices.
- Accuracy: The camcorder was able to capture High Definition (HD) images with high-resolution quality to determine each location of vehicle lateral placement.

Figure 3. 16 The equipment used in obtaining traffic footage (London Camera Exchange, 2018)

3.5.5. Traffic recordings

Traffic flow was filmed at approximately 10 m intervals along the road sections. The camcorder was tightened at the base plate on the tripod by pushing the lever up to attach it. Then the tripod was opened and levelled on the surface according to the little bubble on the arms of the tripod. Finally, the lever was used to lift the camcorder up or down in order to adjust the correct angle. Before starting the traffic footage record, the video mode was set to landscape mode. To record the best view of vehicle lateral positions, the camcorder was placed on the pedestrian footway/sidewalk and the traffic passing between two levelling staffs were recorded (Figure 3.16 and Figure 3.17).

Figure 3. 17 Installation of camcorder

Figure 3. 18 Levelling staffs

This method of recording the traffic footage reduced health and safety risks in conjunction with cost, time-saving, and data accuracy. Measurements were taken at the road side without going onto the road itself avoiding direct exposure to traffic. This approach was thought to be a safe and time-efficient method compared to previous studies described here. It was also important to hide the levelling staffs, tripod and camcorder as much as possible by positioning them next to poles, guard rails or parked vehicles. The levelling staffs were only required to be position on site during the start of each recording and were removed as soon as possible to reduce any influence on driver behaviour.

The recordings of vehicle positions were done within a specific time range – e.g. between 11:00 and 17:00 hours to avoid varied traffic volumes. The approximate time to record the necessary number of vehicles at each location was 20-25 minutes, which was fairly consistent along the length of road sections.

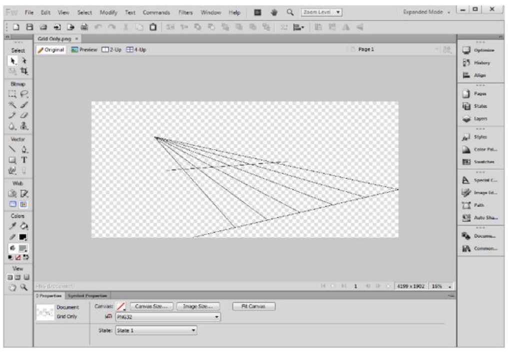
The Annual Average Daily Traffic (AADT) count was recorded and it showed there was little difference in eastbound and westbound lane. It was important to determine the overall information for the traffic loading rather than the traffic loading during the actual time period when the video footage was taken. As such there is a reasonable level of confidence that the traffic flows in each direction and along the entire lengths were consistent, and showed only small variations

3.5.6. Vehicle Placement Measurements

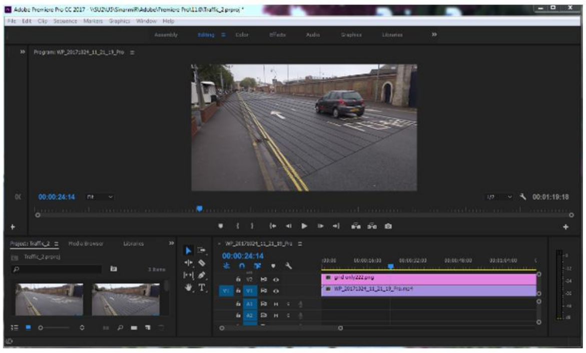
In order to develop the final procedures of superimposing grids to measure the lateral position of each vehicle, pilot studies were conducted. Pilot studies consisted of 4 different trials in pilot study locations.

The first trial was conducted on Gunwharf Road (Figure 3.18) during Autumn 2017. Traffic footage was recorded with a mobile phone from the pedestrian footway. In order to measure the lateral position, single point perspective grid lines were drawn over the image in Adobe Illustrator software as illustrated in Figure 3.19. The grid lines were then exported from Adobe Illustrator software and superimposed with the video record using Adobe Premiere software. The screenshots of the procedures are shown in Figure 3.19. However, the difficulty of this method was the absence of reference points which would cause inaccurate results.

Figure 3. 19 Pilot test site 1: Gunwharf Road, Portsmouth



Exported grid lines



Superimposition method

Figure 3. 20 Exported grid lines superimposed with the video record

The second trial was carried out on St George's Road (Figure 3.20) during Spring 2018. Traffic flow was recorded and transferred to the computer. The difference with this trial was the method used. A board marker was placed on pedestrian footway in order to then extrapolate the grid lines across the road surface using Adobe Illustrator software as shown in Figure 3.21. Nevertheless, this method was not accurate enough to read the position of vehicles due to the lack of precision in placing the grids.

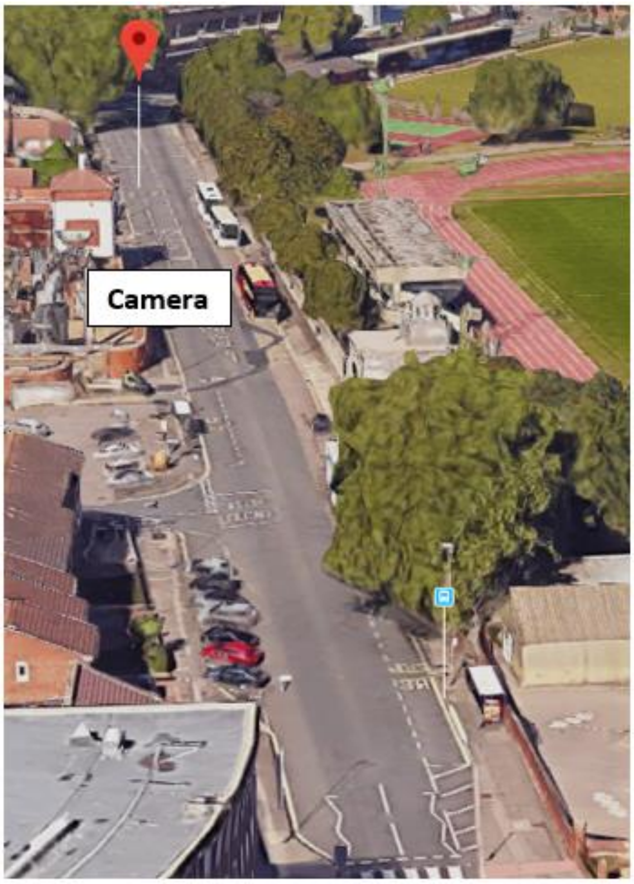


Figure 3. 21 Pilot test site 2: St George's Road, Portsmouth

Figure 3. 22 Vehicle in motion with grid lines placed

A third trial was performed on Portland Street (Figure 3.22). In this method two levelling staffs were placed on the pedestrian footway as a unique identifier for perspective grids to be drawn as shown in Figure 3.23. The main purpose of this method is to check whether the scaling matched with the real-world dimensions by the ratio and proportion calculations. The levelling staffs were fixed temporarily on various points of the road (Figure 3.24). The calculations were then performed according to the distances at intersection points of grids.

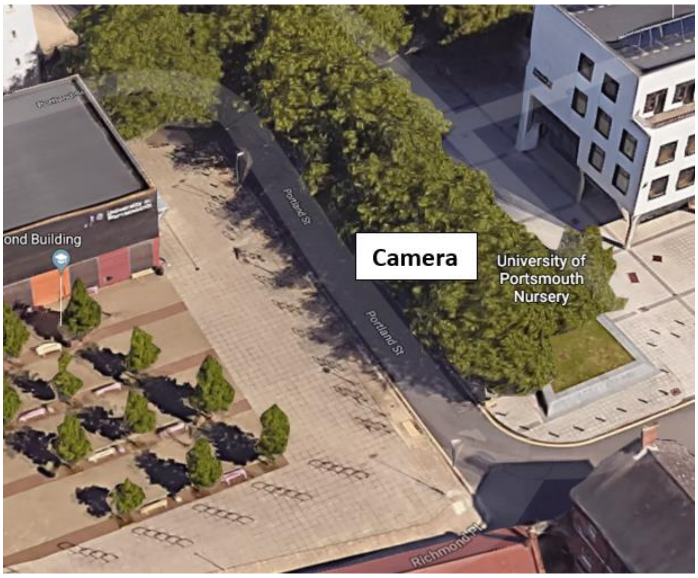


Figure 3. 23 Pilot test site 3: Portland Street, Portsmouth

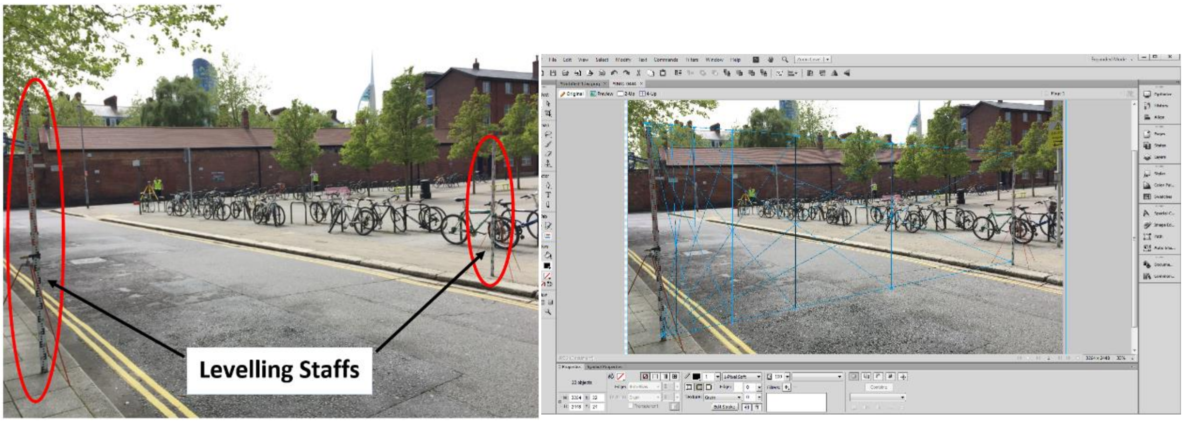


Figure 3. 24 Installation of levelling staffs and perspective grids

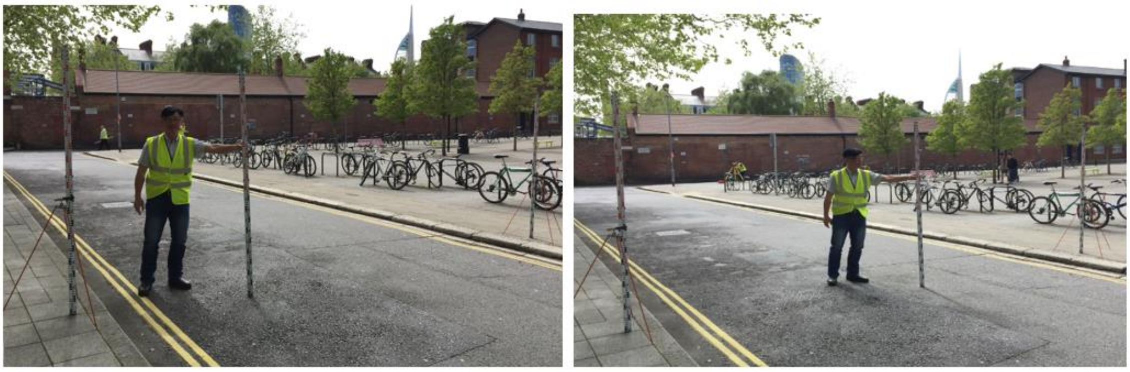
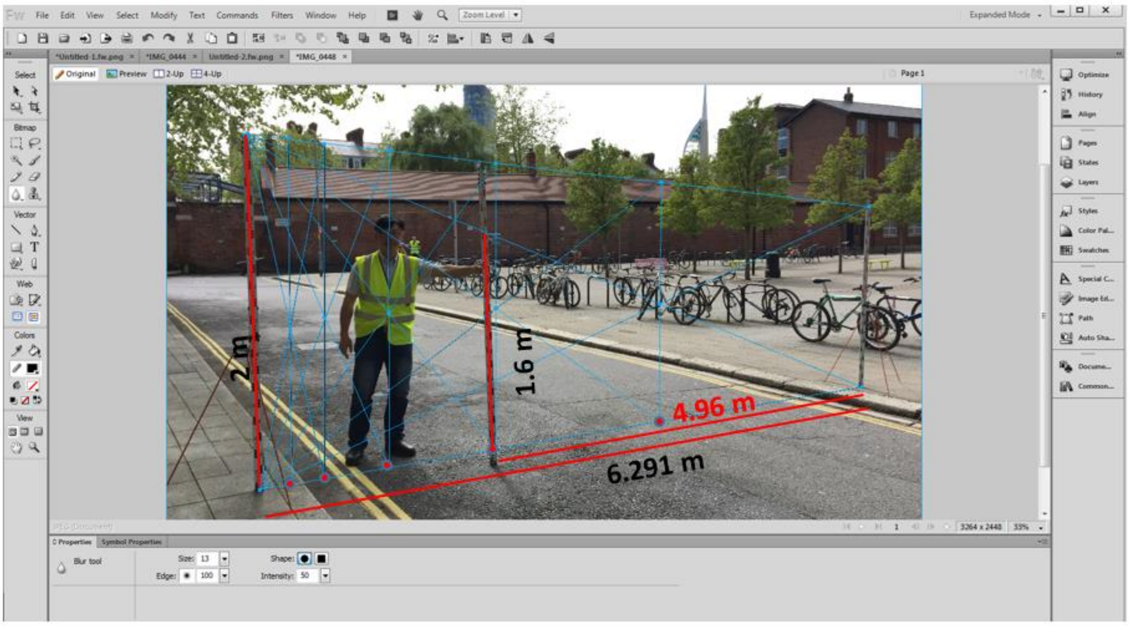


Figure 3. 25 Placing the levelling staffs at different points on the road surface

The road width was measured using a laser metre to be 6.291 metres. The height of the levelling staffs at either side of the road was set at 2 metres. After drawing diagonal lines, the triangle between the central levelling staffs was used to calculate the height of the triangle as 1.6 metres and according to the calculation, the distance between the levelling staff on the road surface and the levelling staff on the right side of the road was 4.96 metres. The same procedure was repeated for the other side of the road and the distance was 1.829 metres. Figure 3.25 illustrates the ratio and proportion calculations made.



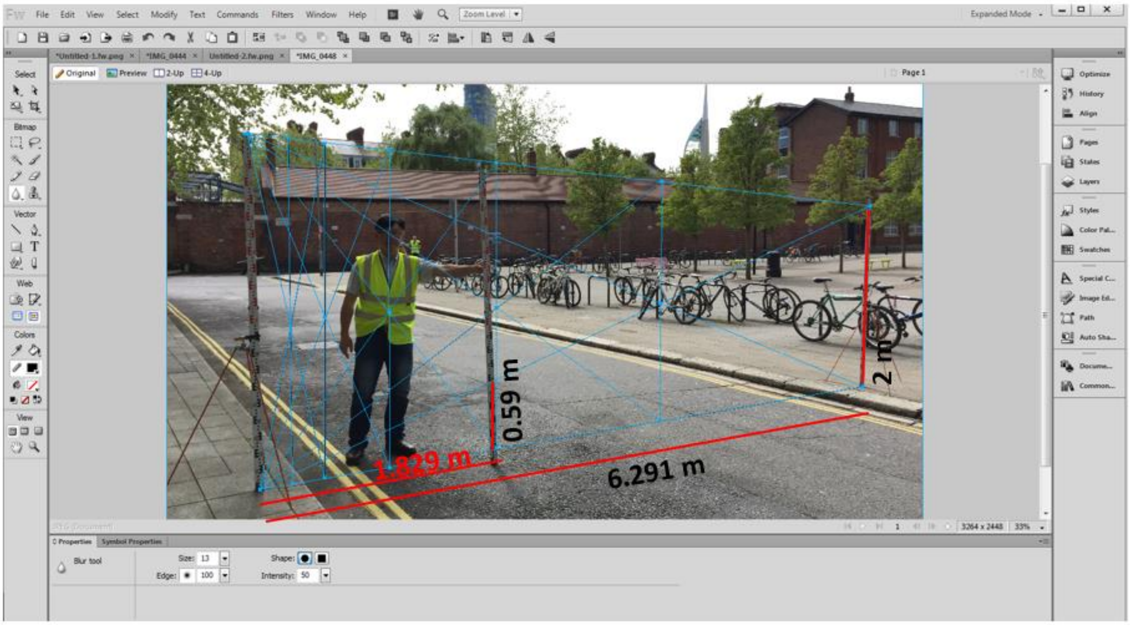


Figure 3. 26 Ratio and proportion calculations

When both distances were added together, the width of the road was calculated to be 6.789 metres. This indicated an error of 6.789 m – 6.291 m = 0.498 m an unacceptable level of accuracy for the study. The reason for that might be the curvature of the road, the position of the levelling staffs or misreading the height of the grid lines on levelling staffs. Therefore, this method refined through a further pilot study where some of these factors could be controlled for.

The fourth and final pilot study was conducted on a pedestrian footway for health and safety reasons (Figure 3.26). In this trial, the levelling staffs were again installed at both sides of the footway. The distance between the two levelling staffs was adjusted to 6 metres. The camcorder was placed 8 metres away in front of the levelling staffs. The footway was marked at every 1 metre interval as shown in Figure 3.27. The point of doing this was to account for the perspective caused by the camcorder being set at an oblique angle to the traffic.

Figure 3. 27 Pilot test site 4: Lion Terrace, Portsmouth

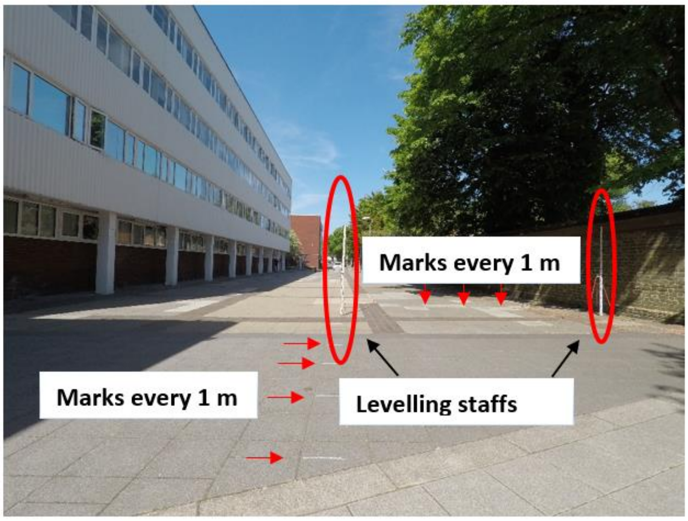


Figure 3. 28 Installation of levelling staffs

The perspective grid lines were then drawn in Corel Draw software using “2-point tool”. The vertical lines were connected by nodes and perpendicular to the snap points. The vertical lines were then used to calculate the ratio to find whether the position of each line is on the correct point in real dimensions. The first grid lines were drawn and 17 perpendicular lines were obtained (Figure 3.28). The distance between the left levelling staff and the 9th perpendicular line on the marked point was calculated as 3.17 metres.

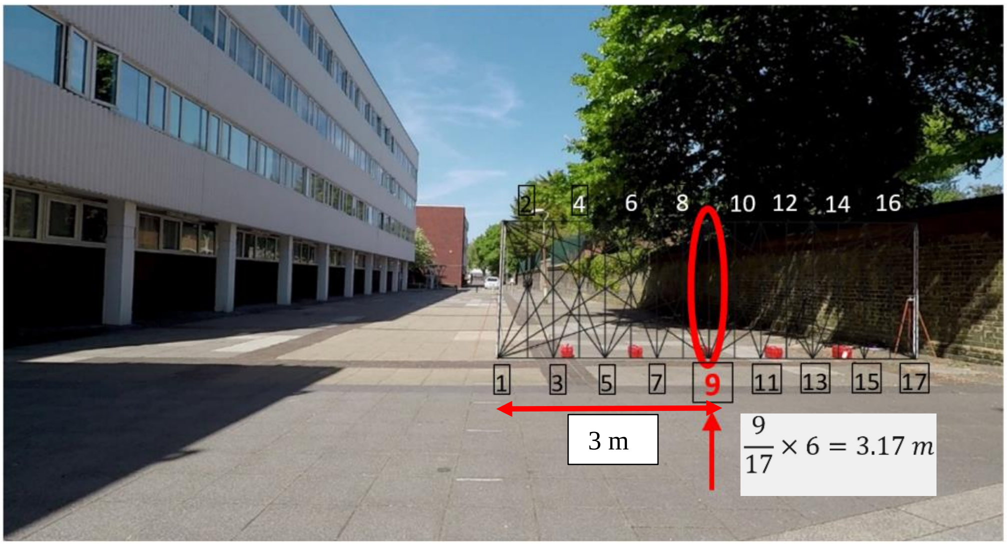


Figure 3. 29 Grid lines in Coral Draw

However, the results again showed that the margin of error associated with the calculations were considered not to be accurate enough. Therefore, the same procedure was repeated by drawing more grids and vertical lines in smaller increments until a reasonably small margin error was obtained. The illustrations are presented in Figure 3.29, Figure 3.30 and Figure 3.31.

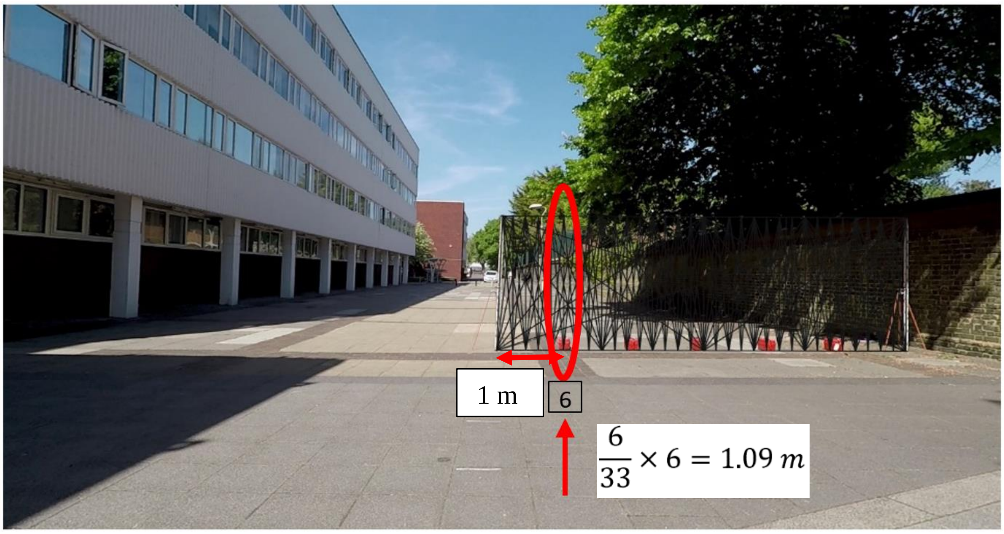


Figure 3. 30 Grid lines in Coral Draw

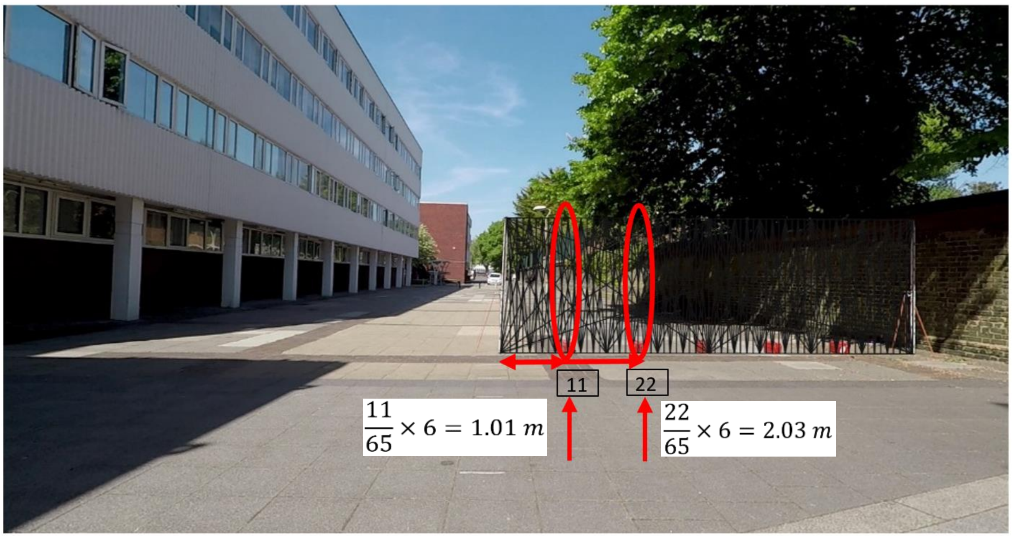


Figure 3. 31 Grid lines in Corel Draw

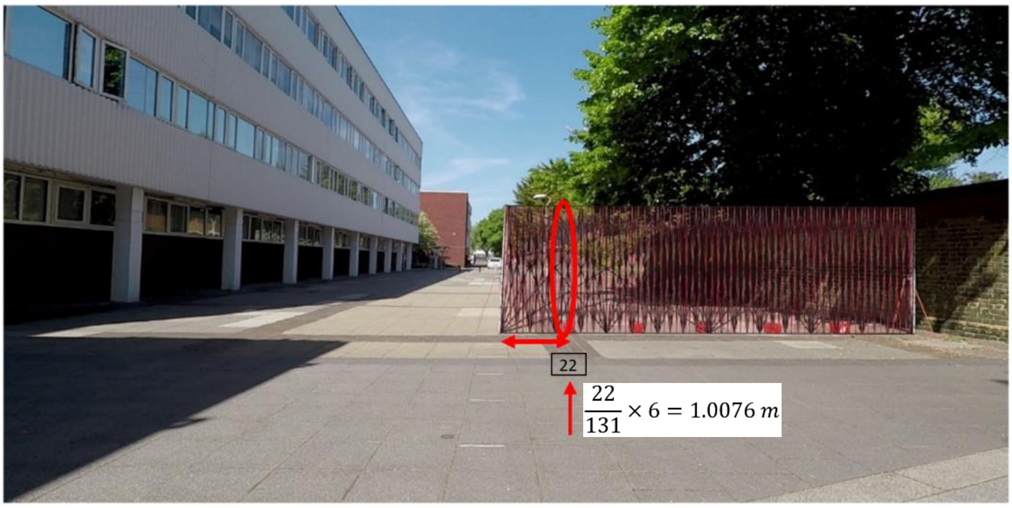


Figure 3. 32 Grid lines Corel Draw

It can be seen that the error associated with the measurement method tested was only 1 mm (0.0076 m) in every 1 m. However, measuring the position of each wheel in the field, it was not possible to achieve such a fine level of precision due to shading and quality of image captured from the video. The precision of the measurements varied between 53 mm and 45 mm for the narrowest and widest lane widths, respectively. For the average lane width, the precision was taken nearest 51 mm. With varying road widths, the precision of the measurements also varied given that the precision relates to the width compared to the (constant) number of increments that the road width is divided into. The level of precision of the measurements obtained in this method is higher than the study conducted by Aydin and Topal (2016) with 20 cm, and by Stempihar et al. (2005) with 3 inches (7.62 cm).

From the recorded traffic footage, the positions of vehicles were measured using this photogrammetric technique to account for the perspective caused by the recording being taken from an oblique angle. A perspective grid was drawn between the two levelling staffs in AutoCAD. Levelling staffs with a fixed height were positioned at each edge of the road for every observation site during recording. A perspective grid consisting of 256 increments of equal distance was drawn in AutoCAD for the initial frame (image) of each recording. The perspective grid was then superimposed over the video using Adobe Premiere software. Each position of vehicle was measured by manually pausing the video each time when a vehicle was passing through the grid lines. This process was supported by two paid assistants. The number of increments from the road edge to the start of the left-hand wheel of the vehicle was read and distance relative to the lane or road markings was calculated. The validation of the data extracted by the assistants was done by looking at randomly successive passing 5 vehicles' lateral position in each video footage to check if it was recorded correctly. In addition, 10 entire videos were analysed by the researcher to validate the data. The final validation was also done when the data was entered to statistical analysis software to be analysed to check if there were any anomalies with the standard deviations of lateral position of vehicles from each location. To keep the environmental factors such as any differences in weather conditions and sunlight/shadow as minimal as possible, the traffic video was recorded in dry weather with no rain and the positions of vehicles were read from a clear vantage point.

The process of measuring the lateral position of vehicles is shown in Figure 3.32.

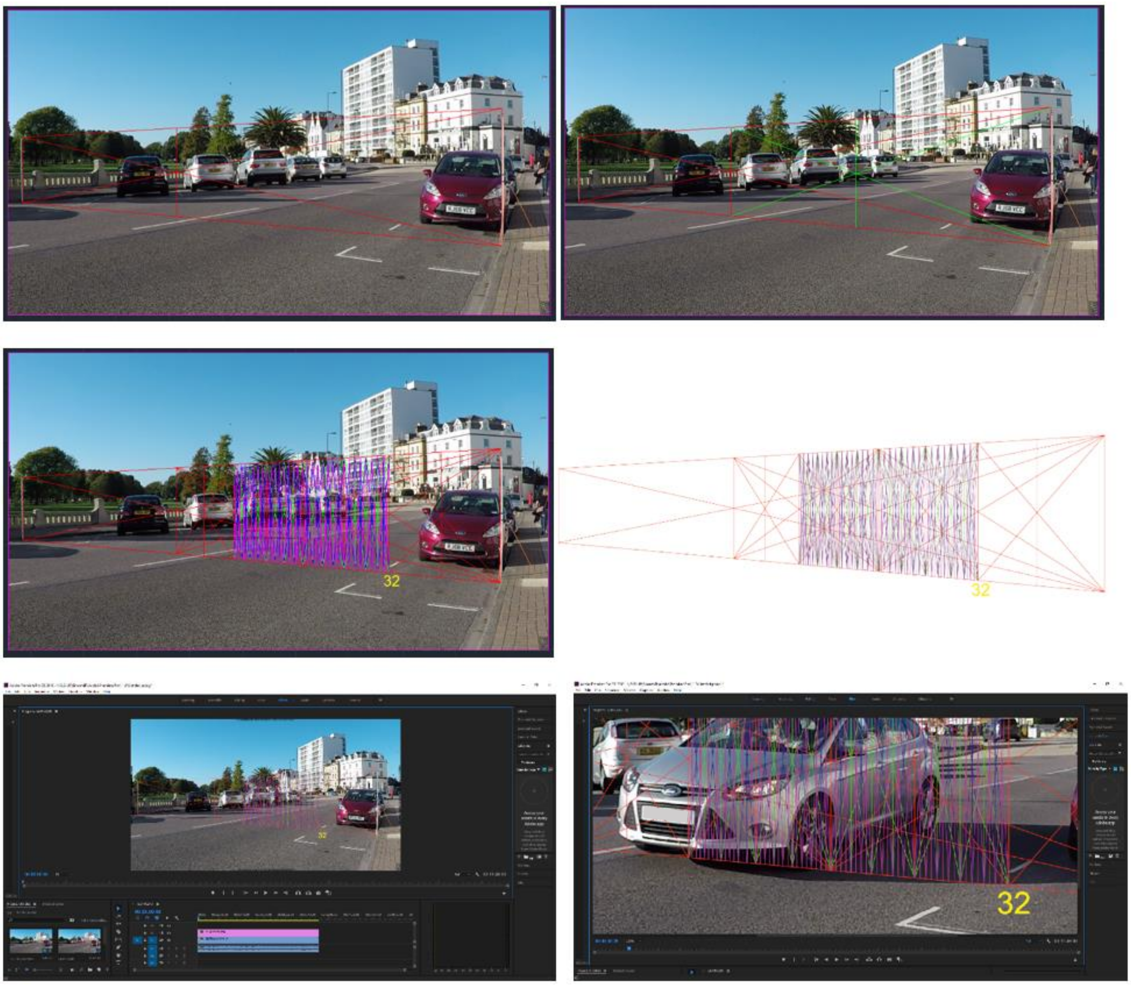


Figure 3. 33 The process of measuring lateral position of vehicles

The real-world dimensions of the increments were then calculated by converting the number of each increment to the distance in metres based on the recorded lane width of each site, measured with a laser measuring device. In Figure 3.32, the number of increments from the nearside kerb to the inner face of the front nearside wheel was 67. The real-world measurement of the road width is 14.15 m and the grid consist of 256 increments. Thus, the real-world position of the left-hand wheel of the vehicle relative to the nearside road edge is calculated as $\frac{14.15}{256}$ x 67 =3.70 m. The collecting and processing of traffic footage data is explained in the next chapter, Data Collection.

3.6. Sampling

Sample size calculation is an essential methodological step before the data collection in order to draw valid conclusions from the results of a study. In essence, this depends on the choice of sampling technique. In general, sampling techniques can be divided into two types (Taherdoost, 2016), as follows:

- Probability or random sampling: This involves random selection and allows making statistical inferences about the whole population to be made.
- Non-probability or non-random sampling: This involves non-random selection based on convenience or other criteria and enables a non-representative sample or a sample with particular characteristics to be selected.

Based on the theoretical framework of the study, and to achieve the research objectives, a purposive sampling technique was selected. This method relies on the judgement of the researcher depending on the research problem and the type of information needed (Tongco, 2007). The idea behind purposive sampling is to concentrate on particular characteristics that are vital and cannot be missed out, which is the case in this project.

To obtain variation in the lateral positions of vehicle data, traffic flow was filmed at approximately 10m intervals along the case study road to coincide with the reported intervals of SCANNER survey data from COLAS Ltd. This method was repeated at 100 different locations. This enabled variations in the geometries of roads and the presence of road features to be included in the dataset.

3.6.1. Power and Sample Size

In order to obtain a statistically significant difference in the lateral placement of vehicle data, a two-variances test was carried out in Minitab to determine the number of vehicles at each location of traffic flow recording required. The standard deviation of vehicle positions was used as the measurement of the lateral wander of vehicles at each location.

The use of a two variance test is to examine the relationship between power, sample size, and the ratio to compare two population variances or standard deviations to a target or reference value (Minitab Support, 2019). The following quantities are involved in sample size selection for this test (Minitab Support, 2019; Sleeper, 2012):

- Power: The probability of being able to detect an effect of the specified size. The selected power value indicates the percentage chance of detecting a difference between two population variances or standard deviations.
- Sample size: The number of observations to be measured at each sample. For a two-sample test, this is the size of each sample.
- Ratio: The ratio between population variability values.
- Significance level: This is the value of alpha (α) which is used to set the test. The significance level is often 0.05, although larger or smaller values might be appropriate.

A small number of road site locations were used to generate some typical standard deviation of lateral vehicle position data that could be used for the power analysis. In this research, a 1.35 ratio $\left(\frac{Standard\ Deviation1}{Standard\ Deviation\ 2} = 1.35\right)$ was used to calculate the number of vehicles required. The power value of 80% chance of detecting statistically significant differences was also entered. The results indicated that the positions of 105 vehicles needed to be recorded from each road section. Figure 3.33 shows the resulting report in the Minitab session window. This means that there is an 80% chance of detecting a 95% statistically significant difference in standard deviations where the difference is at least a ratio of 1.35 and the sample size is105 vehicles at each location.

```
Power and Sample Size

Test for Two Standard Deviations

Testing (StDev 1 / StDev 2) = 1 (versus ≠)
Calculating power for (StDev 1 / StDev 2) = ratio
α = 0.05
Method:  Levene's Test


       Sample  Target
Ratio    Size   Power  Actual Power
 1.35     105     0.8      0.803484

The sample size is for each group.
```

Figure 3. 34 Power and Sample Size calculation for two standard deviations

The 105 recordings at each of the 100 locations mean that the positions of 10,500 vehicles needed to be determined.

3.7. Chapter Summary

Research scope, method of data collection and design of observation are the base for building the required data set for this study. In a practical application, building a good data set is an essential requirement to develop reliable models.

The final method was to measure the positions of 105 vehicles recorded at 100 different locations (10,500 vehicles in total) using a photogrammetric method. The precision of the method was 50 mm.

Secondary data was provided from COLAS Ltd. The secondary and primary data were then combined by superimposing the locations of data collected to test for any significant differences or associations between channelisation and rutting as explained in the next chapter.

Chapter 4 Data Collection and Collation

4.1. Introduction

This chapter describes the observational data collection exercise. The secondary data is also explained, which was obtained from COLAS Ltd to coincide with the reported intervals of SCANNER survey data. Summaries of all data are then presented.

4.2. Measurements of the degree of channelisation

In order to measure the position of vehicles, the traffic flow was recorded on a two-lane single and on a dual two-lane carriageway from Clarence Parade and South Parade A288 (Figure 4.1) and repeated at 100 different locations along the road section length between July and November 2018.

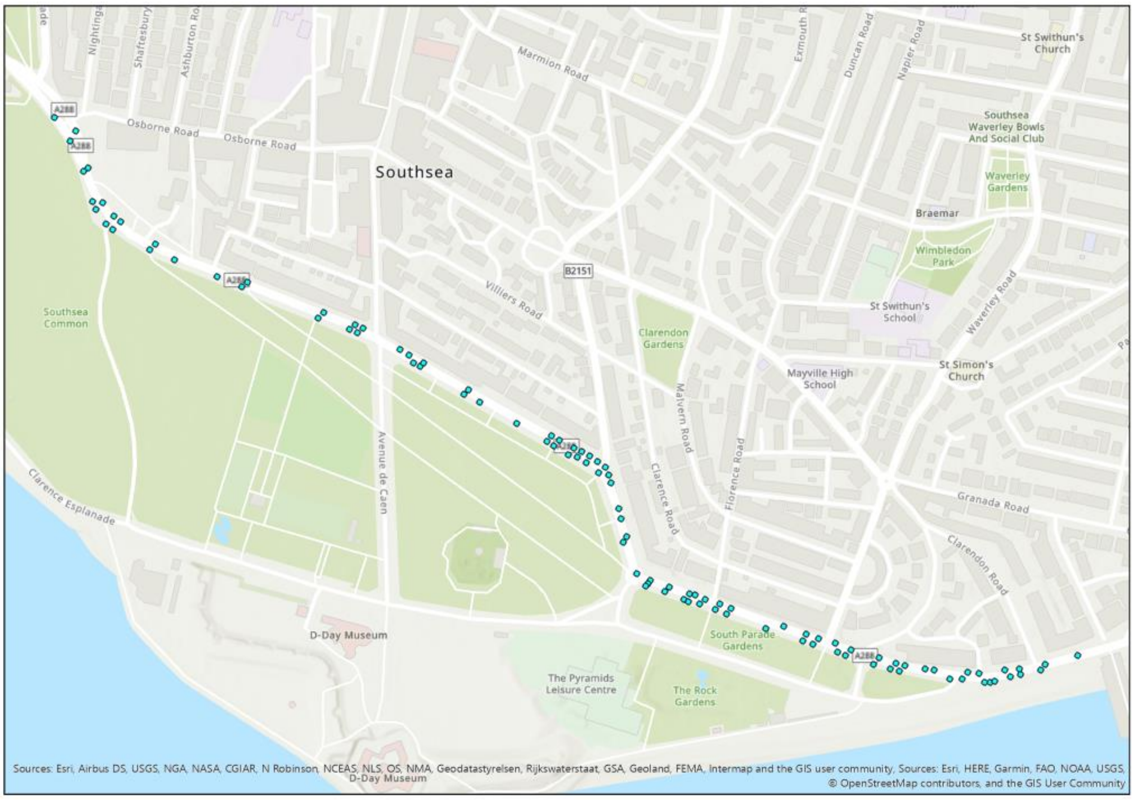


Figure 4. 1 Clarence Parade and South Parade A288 observation site

By selecting these 100 locations, at approximately 10 m intervals to keep safe high visibility and to avoid any junction, it was possible to gain variation in following:

- Presence of a nearside parked vehicle,
- Presence of a nearside cycle lane,
- Presence of zig-zag road markings,
- Presence of nearside hatching,
- Presence of a central reservation,
- Road and lane widths.

The features were recorded visually as either being present or not (binary) at the immediate location of the observation. Road widths and lane widths were measured using a laser distance metre device (Leica DISTOTM X310), with road width being the kerb to kerb distance and lane width being between the nearside and offsite lane markings. A manual classified traffic count was performed using handheld tally counter for half an hour period both in the morning (08:15-08:45) and evening peak (17:00-17:30) times to ensure the composition of vehicle does not change along the length. The traffic flow speed survey was carried out with a hand-held speed meter camera (Unipar SL700®). The observations were done for 30 vehicles in various locations where the arterial roads intersected with the main road. The reason behind this was to ensure the vehicle composition is constant along the road length. Also, the number 30 also comes from an examination of the chi-square distribution. For normally distributed data, approximately 30 observations are needed to have reasonably short confidence bounds on the variance estimate (Kar & Ramalingam, 2013). The equipment used in the survey process are shown in Figure 4.2.

(a) Speed camera (b) Laser meter (c) Tally counter

Figure 4. 2 The equipment used in the survey

In order to measure the degree of channelisation, the traffic video data were collected and processed for 100 different road sections. The video recordings at the 100 locations amounted to 50 hours of footage in total as indicated in Table 4.2. In terms of the number of vehicles, there were 10,500 vehicles for which the lateral positions were recorded. In addition, the detailed information for each road section such as the presence of road site features are shown. It can be clearly seen that there was variation in the geometric characteristics between the road sections. Descriptive statistics are shown in Chapter 5.

Sections, with the narrowest and widest road/lane widths are shown in Figure 4.3. After analysing each traffic video with the superimposition technique (as described in the methodology chapter), the lateral position of vehicles was entered into Microsoft Excel in order to obtain the standard deviations at each location. The standard deviation of the first 105 vehicles passing through each road section was calculated as the measure of the degree of channelisation. The excel spreadsheet prepared for this process is presented in Table 4.1.

Table 4. 1 The excel spreadsheet used to process collected lateral position of vehicles

Location		
Date / Time of the day		
Road width (m)		
Lane width (m)		
Each increment (m)		
Standard deviation		
Vehicle	**Number of increments from kerb**	**Distance from kerb line (m)**
1		
2		
3		
…		
…		
103		
104		
105		
Mean		
Standard deviation		

Table 4. 2 Summary of traffic video data

Test Sites	Unit		Number of sites with particular road features									
			Parked vehicle	No parked vehicle	Cycle lane	No cycle lane	Zig-zag road markings	No zig-zag road markings	Nearside hatching	No nearside hatching	Central reservation	No central reservation
Clearance Parade	Recording time	26 hrs										
	Total vehicles	5460	14	38	5	47	6	46	2	50	25	27
South Parade	Recording time	24 hrs										
	Total vehicles	5040	10	38	5	43	7	41	13	35	9	39
Total recording time: 50hrs; Total vehicles: 10,500												

(a) Road sections with narrowest lane width (3.40 m – 3.88 m)

(b) Road sections with widest lane width (14.20 m – 10.65 m)

(c) Road sections with narrowest road width (5.50 m – 6.20 m)

(d) Road sections with widest road width (22.70 m – 17.82 m)

Figure 4. 3 Road sections with narrowest and widest lane/road width

4.3. Rutting deterioration data

Rutting data were extracted for each section from a relevant SCANNER survey dataset, provided by COLAS Ltd. The SCANNER data were collected for different traffic lanes and directions for different years. The rut depths obtained from COLAS were for nearside (left) wheel paths and offside (right) in millimetres averaged over 10 m lengths. Nearside and offside rut depths are known to differ due to the cross sectional profile (camber) of the pavements and the different dimensions of wheel tracks. This means that in most instances the nearside ruts are deeper than the offside ruts (D.-H. Chen & Hugo, 1998; J. van der Walt, Scheepbouwer, & Tighe, 2018). Observations by the Transport Research Laboratory confirmed that nearside rut depths were on average about 20% higher than those on the offside (Potter & O'Conner, 1989).

When considering the lifespan or condition of a pavement, the average of deterioration across the pavement is not of interest. What is important is that no section of the pavement falls below a certain level of performance. Hence, the nearside rut is usually the determining factor in the overall rut level on a road section. As such, in this study the nearside rut was used in the analysis, rather than the offside.

The SCANNER dataset also includes other potential explanatory factors for each of the 100 locations as follows:

- East or west bound traffic lane.
- Year of rut depth data (2014, 2017, 2018).
- Camber (% cross fall).
- Horizontal curvature (radius of curve).

To match the primary data chainages with rutting data chainages, ArcGIS softaware was used to overlay rutting data onto the data collected in the field. The 100 observation points were matched to the corresponding rut depths through the use of ArcGIS software and the coordinates of each point as shown in Figure 4.4.

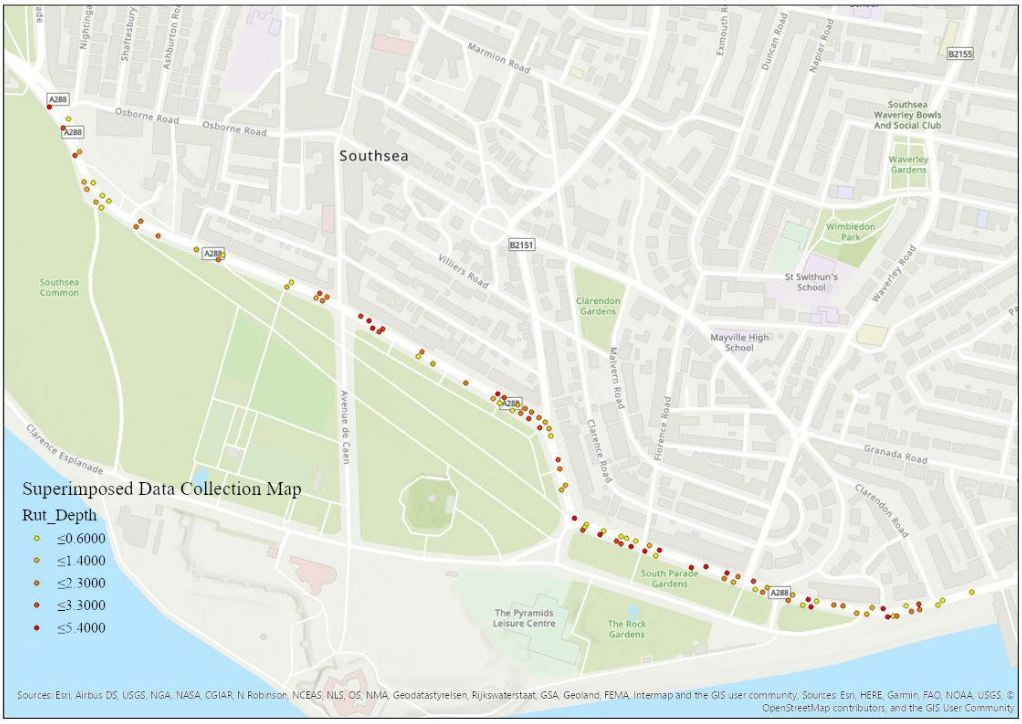


Figure 4. 4 100 nearside rut depths used in the analyses

4.4. Chapter Summary

This chapter summarised the collection and processing of traffic footage data for further analysis explained in Chapter 5.

Chapter 5 Results and Analysis

5.1. Introduction

This chapter presents the results gathered from the data collection exercise, tests the data for statistically significant difference and associations before finally describing channelisation and rut depth thorough regression equations.

5.2. Road geometry and channelisation

After the lateral placement of vehicles for each road section was entered into spreadsheets and standard deviations calculated (as a measure of lateral wander of vehicle positions/degree of channelisation), the results were compared to those found in the literature and then analysed to investigate how road geometries relate to channelisation.

5.2.1. Degree of Channelisation

The standard deviations of vehicle position data represent the degree of channelisation (lateral wander of vehicle positions) at each of the 100 observations sites, as shown in Figure 5.1. The standard deviations of vehicle placement for all 100 road sections were greater than those found in the studies conducted by Timm and Priest (2005), Buiter et al. (1989), Blab and Litzka (1995) and (Erlingsson et al., 2012). The smaller standard deviations of vehicle placement in the study by Timm and Priest (2005) was due to the use of a test track in a closed-access facility restricted to only 10 drivers. The test track was also a closed loop and the repetitive environment would have caused the vehicles to travel consistently along the same line, thus leading to small standard deviations of vehicle positions compared to the real-world data used in this study. The standard deviations at the different road sections ranged in this research from 130 mm to 858 mm. Also, the composition of vehicles recorded differed from those in the literature. Timm and Priest (2005) used only 2 test vehicles that were both heavy goods vehicles.

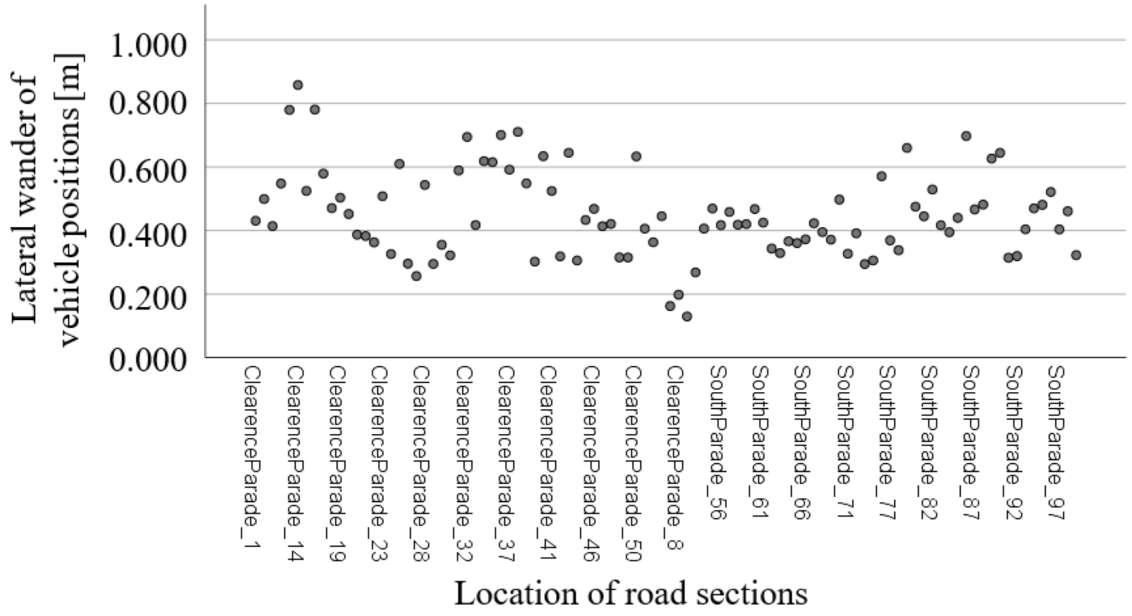


Figure 5. 1 Scatterplot of the lateral wander of vehicles observed

The variation in the degree of channelisation was recorded, which allows analyses to be undertaken to determine whether this variation related to the geometries of the road sections.

5.2.2. Distribution of lateral position of vehicles

The vehicle positions at each of the 100 observation points were found to approximate to a normal distribution. Figures 5.2 to 5.4 show the distributions at a number of locations, with different geometric characteristics. All positions are relative to the left-hand (nearside) road edge.

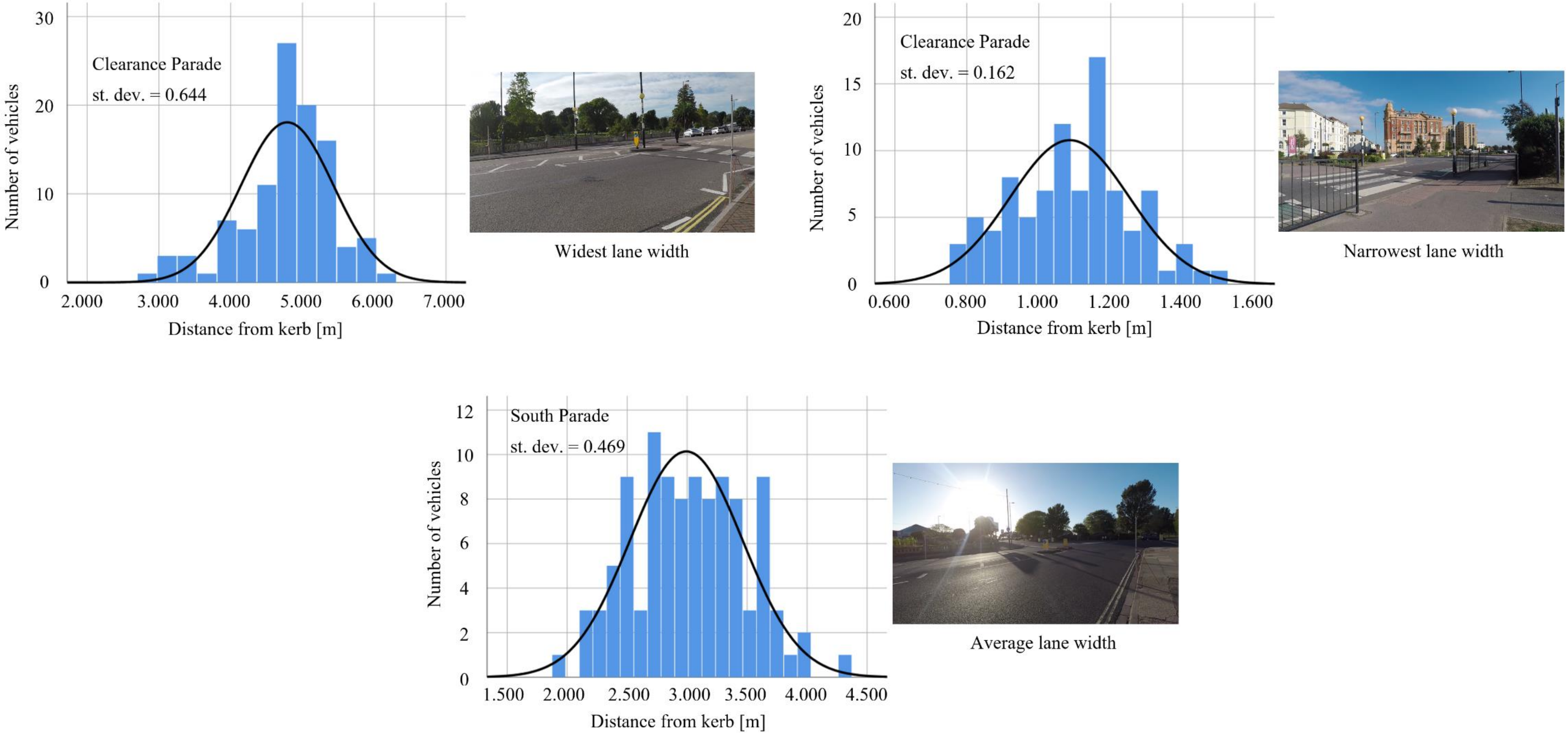


Figure 5. 2 Frequency distributions of lateral placement of vehicles for different lane widths

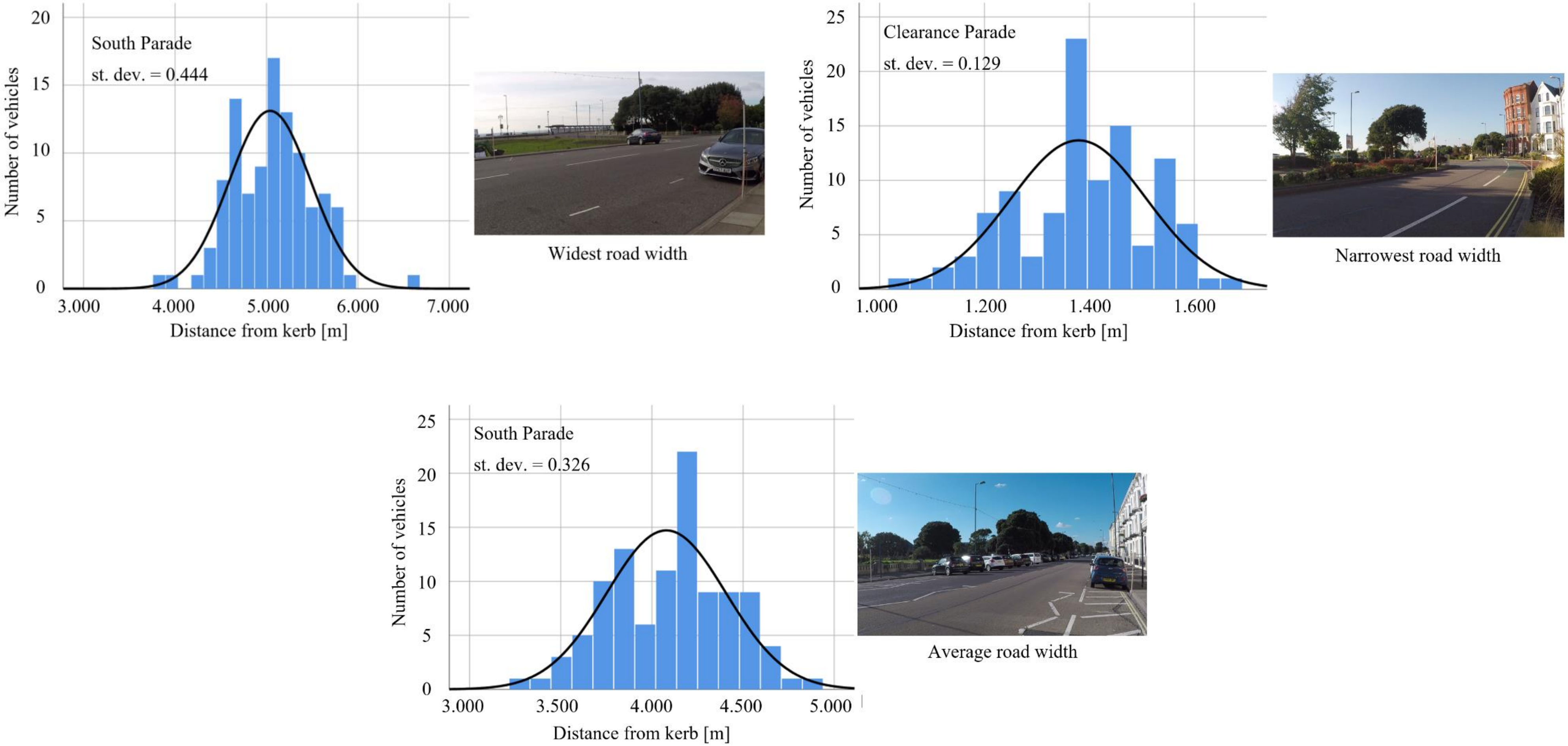


Figure 5. 3 Frequency distributions of lateral placement of vehicles for different road widths

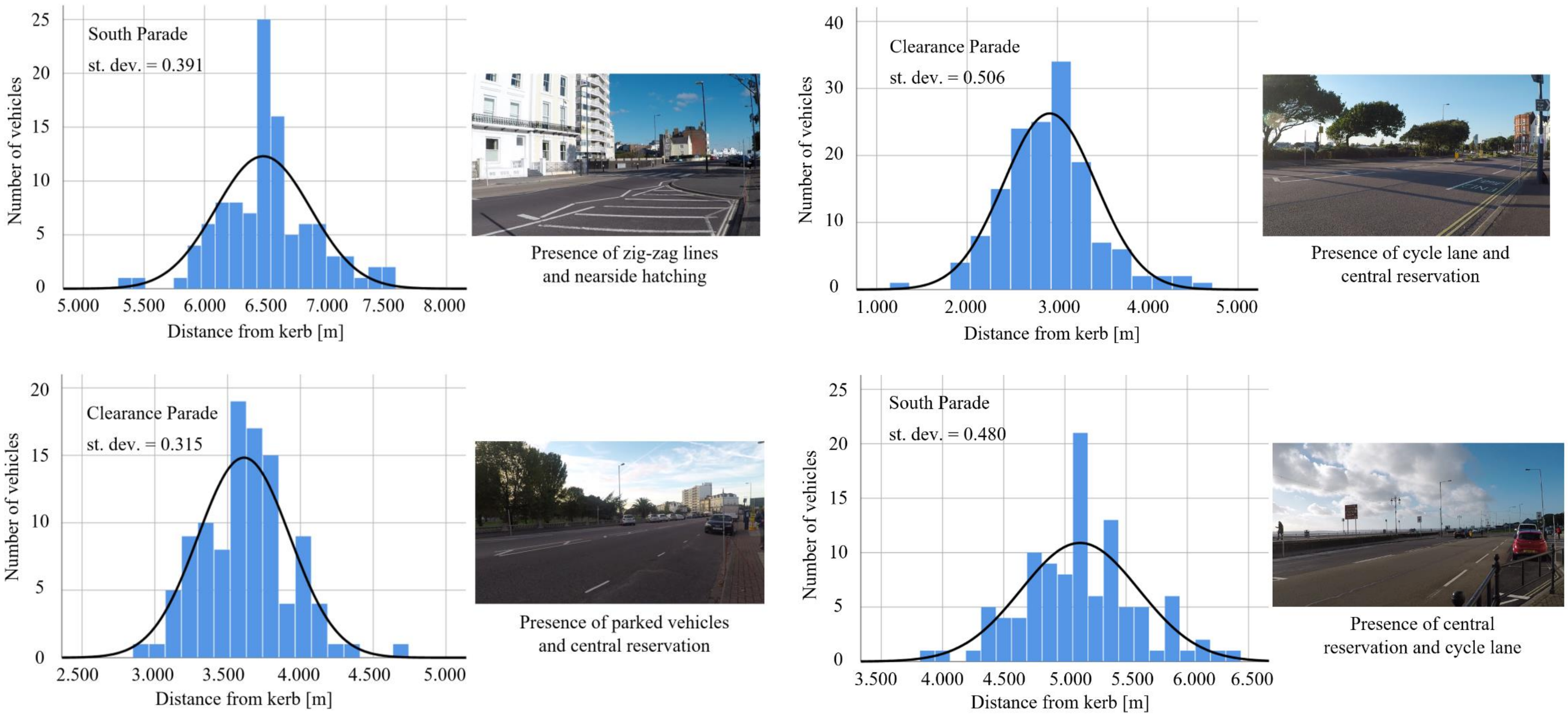


Figure 5. 4 Frequency distributions of lateral placement of vehicles for road sections with particular road features

Many of the statistical procedures used in this study, including tests of correlation, regression and difference of means tests assume that the data follows a normal distribution. The normality of data can be considered visually as presented above or by significance tests (Ghasemi & Zahediasl, 2012). After plotting the frequency distributions for the road sections as shown in Figure 5.2, Figure 5.3 and Figure 5.4, further analysis was carried out to determine whether the distributions at each location was normal. The assessment of normality was completed by conducting a Kolmogorov-Smirnov (K-S) test, as it is the most well-known normality test (Drezner, Turel, & Zerom, 2010; Ghasemi & Zahediasl, 2012). The Explore command was initially employed for testing normality using SPSS statistics software. However, due to the lower power of the test to detect whether samples come from a non-normal distribution, these tests were supplemented by Shapiro-Wilk tests. It has been argued that these tests provide better power than K-S tests for determining the normality of data (Thode, 2002). The test checks the difference between the distribution at each location and a perfectly normal one based on *p*-value. When the *p*-value is 0.05 or higher, there is no statistically significant difference from the normal distribution (Field, 2013). In both sets of tests, the *p*-values were found to be greater than 0.05, which indicates that they were normally distributed in 93 of the road sections. There were 7 road sections (highlighted in Table 5.1) where *p*-values were lower than 0.05. These were investigated further in terms of their symmetry/skewness and kurtosis. According to D. George and Mallery (2010), if the values of symmetry/skewness and kurtosis are between -2 to 2, variables can be accepted as a normal distribution. The other 7 road sections were compared according to this statement, and all were determined to be normally distributed. The results presented in Table 5.1.

Table 5. 1 Results of Kolmogorov-Smirnov and Shapiro-Wilk normality tests

	Tests of Normality				
	Kolmogorov-Smirnov (1) and Shapiro-Wilk (2)				
	Sig. (*p*-value) (1)	**Sig. (*p*-value) (2)**		**Sig. (*p*-value) (1)**	**Sig. (*p*-value) (2)**
Clarence Parade 1	0.076	0.120	**Clarence Parade 51**	0.200	0.997
Clarence Parade 2	0.032	0.059	**Clarence Parade 52**	0.167	0.653
Clarence Parade 3	0.121	0.524	**South Parade 53**	0.054	0.001
Clarence Parade 4	0.200	0.825	**South Parade 54**	0.200	0.474
Clarence Parade 5	0.200	0.879	**South Parade 55**	**0.004**	**0.013**
Clarence Parade 6	0.200	0.254	**South Parade 56**	**0.029**	**0.029**
Clarence Parade 7	0.200	0.397	**South Parade 57**	0.200	0.139
Clarence Parade 8	0.200	0.586	**South Parade 58**	0.115	0.367
Clarence Parade 9	0.027	0.107	**South Parade 59**	0.200	0.366
Clarence Parade 10	0.200	0.369	**South Parade 60**	0.200	0.186
Clarence Parade 11	0.200	0.456	**South Parade 61**	0.200	0.794
Clarence Parade 12	0.200	0.807	**South Parade 62**	0.200	0.517
Clarence Parade 13	0.200	0.965	**South Parade 63**	0.200	0.196
Clarence Parade 14	0.200	0.987	**South Parade 64**	0.200	0.617
Clarence Parade 15	0.007	0.192	**South Parade 65**	0.200	0.674
Clarence Parade 16	0.200	0.906	**South Parade 66**	0.200	0.629
Clarence Parade 17	0.200	0.384	**South Parade 67**	0.200	0.408
Clarence Parade 18	**0.008**	**0.008**	**South Parade 68**	0.200	0.329
Clarence Parade 19	0.200	0.020	**South Parade 69**	**0.001**	**0.009**
Clarence Parade 20	0.026	0.198	**South Parade 70**	0.200	0.022
Clarence Parade 21	0.200	0.241	**South Parade 71**	0.099	0.242
Clarence Parade 22	0.200	0.831	**South Parade 72**	0.200	0.773
Clarence Parade 23	0.034	0.248	**South Parade 73**	0.200	0.237
Clarence Parade 24	0.200	0.522	**South Parade 74**	0.200	0.055
Clarence Parade 25	0.200	0.131	**South Parade 75**	0.200	0.744
Clarence Parade 26	0.114	0.189	**South Parade 76**	0.200	0.810
Clarence Parade 27	0.151	0.053	**South Parade 77**	0.200	0.936
Clarence Parade 28	0.200	0.496	**South Parade 78**	0.200	0.527
Clarence Parade 29	0.200	0.452	**South Parade 79**	0.200	0.094
Clarence Parade 30	0.200	0.415	**South Parade 80**	0.200	0.518
Clarence Parade 31	0.056	0.157	**South Parade 81**	0.119	0.139
Clarence Parade 32	0.200	0.431	**South Parade 82**	0.200	0.575
Clarence Parade 33	0.200	0.191	**South Parade 83**	0.200	0.474
Clarence Parade 34	**0.007**	**0.005**	**South Parade 84**	0.200	0.381
Clarence Parade 35	0.200	0.293	**South Parade 85**	0.200	0.143

Clarence Parade 36	0.200	0.818	**South Parade 86**	0.200	0.746
Clarence Parade 37	0.200	0.587	**South Parade 87**	0.200	0.340
Clarence Parade 38	0.200	0.371	**South Parade 88**	0.200	0.100
Clarence Parade 39	0.200	0.567	**South Parade 89**	0.200	0.983
Clarence Parade 40	0.200	0.370	**South Parade 90**	0.200	0.923
Clarence Parade 41	0.200	0.894	**South Parade 91**	0.200	0.500
Clarence Parade 42	0.200	0.574	**South Parade 92**	0.200	0.204
Clarence Parade 43	0.200	0.592	**South Parade 93**	0.200	0.240
Clarence Parade 44	0.200	0.114	**South Parade 94**	0.200	0.996
Clarence Parade 45	0.200	0.468	**South Parade 95**	0.200	0.519
Clarence Parade 46	0.200	0.905	**South Parade 96**	**0.030**	**0.030**
Clarence Parade 47	0.044	0.078	**South Parade 97**	0.200	0.770
Clarence Parade 48	**0.001**	**0.000**	**South Parade 98**	0.165	0.123
Clarence Parade 49	0.200	0.484	**South Parade 99**	0.200	0.400
Clarence Parade 50	0.179	0.064	**South Parade 100**	0.148	0.092

5.2.3. Descriptive Statistics

Descriptive statistics are the numerical and graphical techniques used to organise, present and analyse data. To investigate the effect of the road geometry and the roadside features on the lateral distribution of vehicles, descriptive statistics were extracted from SPSS and organised by variable type. Table 5.2 and Table 5.3 summarise the data.

Table 5. 2 Descriptive statistics of scalable variables observed in this study

Road geometries (m)				
	Minimum	Maximum	Mean	Standard deviation
Lane width	3.40	14.19	6.46	1.82
Road width	5.50	22.70	14.70	2.92

The dependent variable of lateral wander of vehicle positions was measured from a minimum of 130 mm to a maximum of 858 mm with a standard deviation of 137 mm, as described in section 5.2.1.

Table 5. 3 Descriptive statistics of nominal measures obtained in this study

Presence of road features		n
Parked vehicles		
	parked vehicles	24
	no parked vehicles	76
Central reservation		
	present	34
	not present	66
Nearside hatching		
	present	16
	not present	84
Zigzag lines		13
	present	13
	not present	87
Cycle lane		
	present	10
	not present	90

Table 5.2 presents the maximum and minimum values for both lane and road width. The variation in the range for lane width is 10.79 m and for road width 17.2 m. The standard deviation is 1.82 m for lane width and 2.92 m for road width.

One of the assumption that underpins many statistical tests such as linear regression analysis is for each of the continuously distributed independent variables to be normally distributed (Alexopoulos, 2010). The normality of all variables was tested using Kolmogorov-Smirnov (K-S) and Shapiro-Wilk test. Based on K-S and Shapiro-Wilk test results dependent variable of lateral wander of vehicle positions and independent variable of lane width are normally distributed. The other independent variable of road width was not normality distributed even when checked for skewness and kurtosis which was not between -2 and 2. However, according to Altman and Bland (1995) when a continuous dependent or independent variable is very non-normal (e.g. extremely skewed) and used in linear regression, then it is unlikely that the residuals will by normally distributed. This would mean that the model fitted to the data is sub-optimum. Whilst the tests for road width indicate it is not normally distributed, it is neither highly skewed nor highly non-normal. However careful attention should be paid to the residuals of the regression analyses described in section 5.2.6. The summary of test results is shown in Table 5.4. The frequency distribution plots are also illustrated in Figure 5.5. for lane width and road width and in Figure 5.6 for lateral wander of vehicle positions.

Table 5. 4 Results of Kolmogorov-Smirnov and Shapiro-Wilk normality tests

Tests of Normality	Lateral wander of vehicle positions	Lane width	Road Width
Kolmogorov-Smirnov (K-S) test	0.028	0.530	**0.000**
Shapiro-Wilk test	0.035	0.000	**0.000**

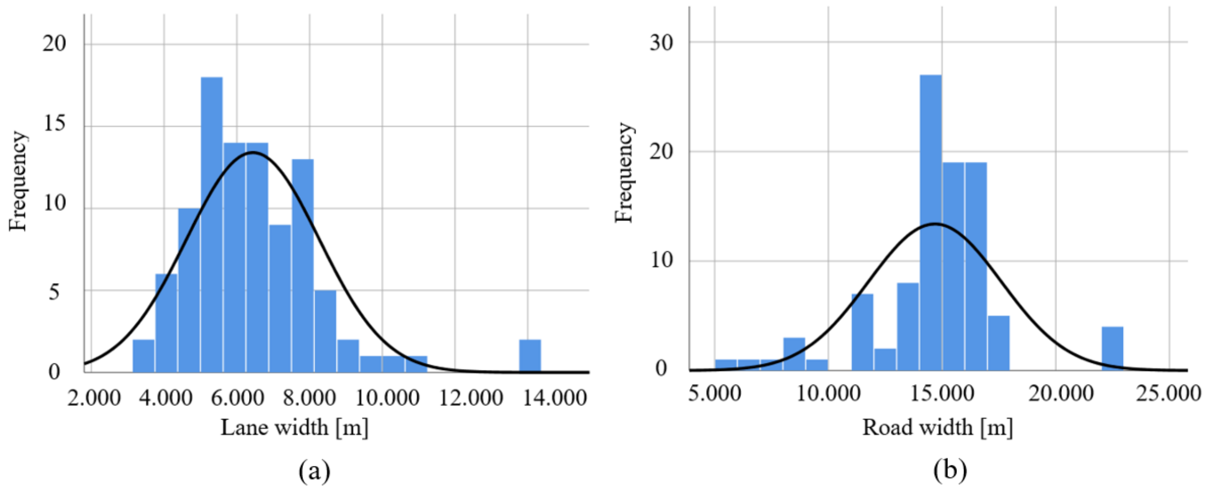


Figure 5. 5 Frequency distribution of the (a) lane width and, (b) road width

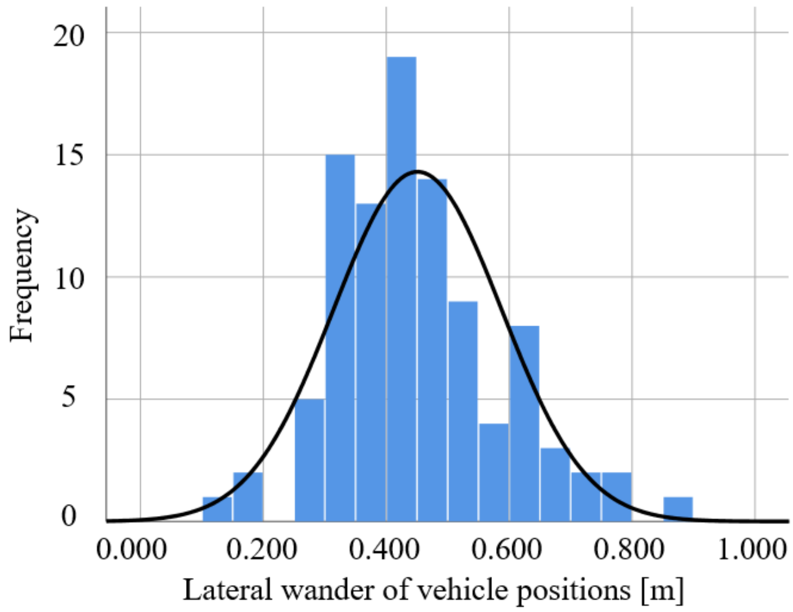


Figure 5. 6 Frequency distribution of lateral wander of vehicle positions

The descriptive statistics showed that the sampling method adopted in this study resulted in a good degree of variation in both the independent and dependent variables, which enables analyses to be undertaken into how differences in the independent variables relate to differences in the dependent variable.

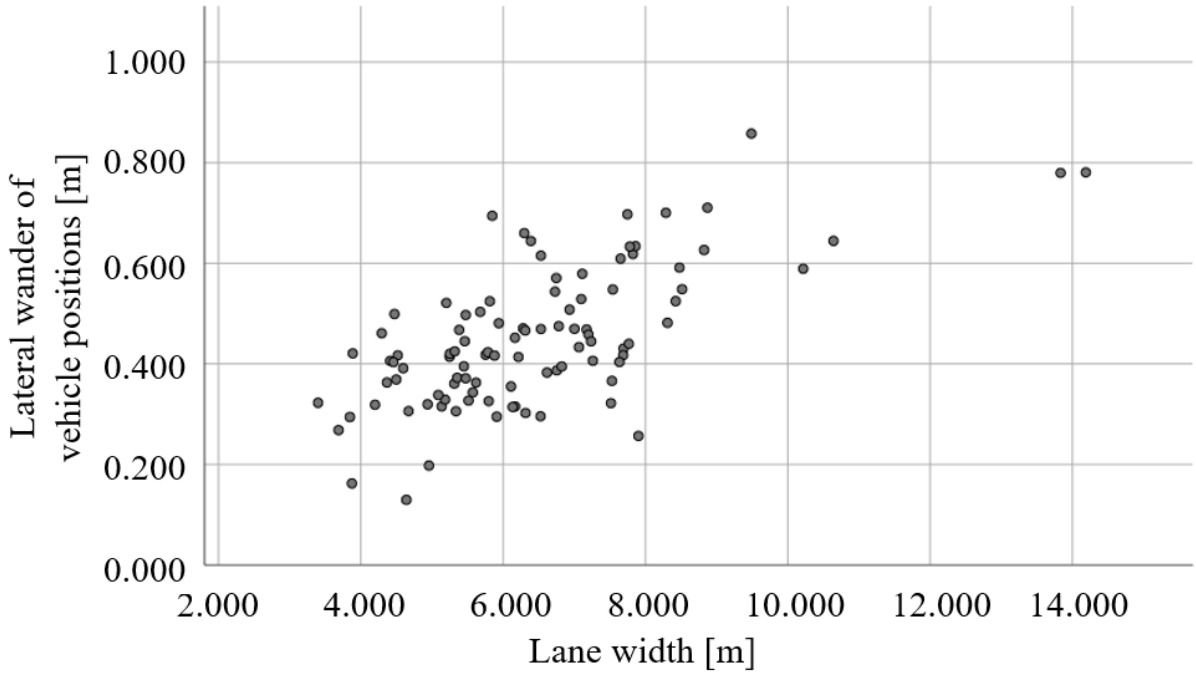
5.2.5. Bi-variate Correlation Tests

Correlation analyses were used to examine the relationship between degrees of channelisation (lateral wander of vehicle positions) and all independent variables.

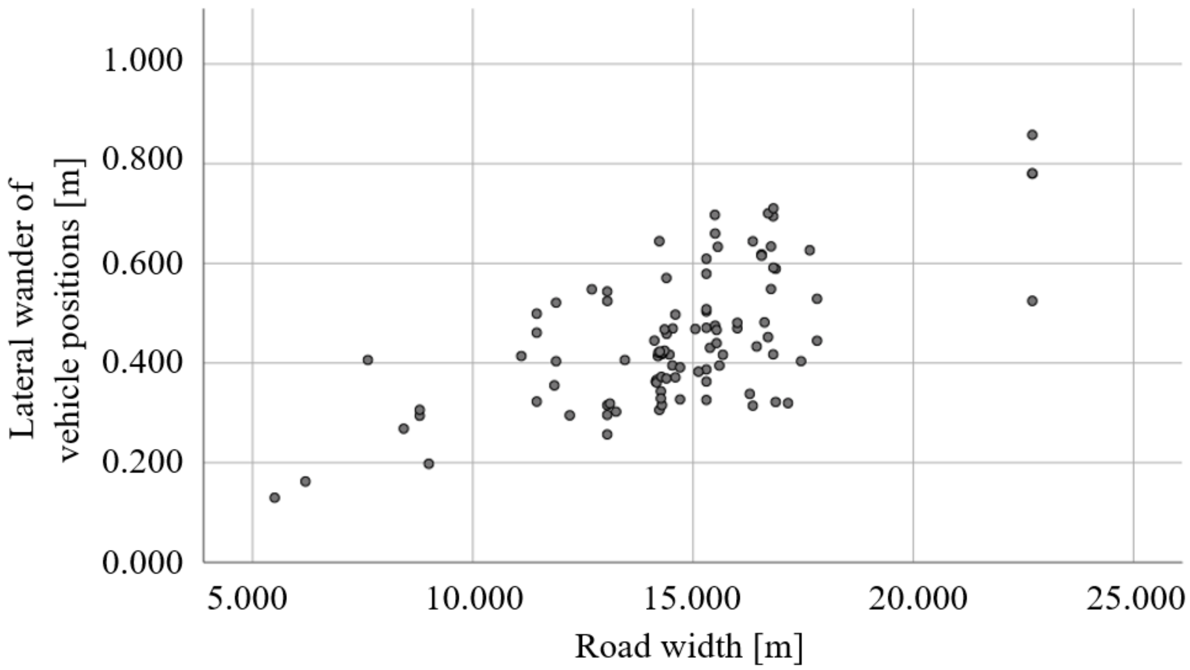
A parametric Pearson Correlation statistic was calculated to assess the correlation between degree of channelisation (lateral wander of vehicle positions) and both lane width and road width. The Pearson *r* indicates the magnitude and statistical significance of any bivariate associations. For those variables that are continuous (interval/ratio data) the Pearson *r* statistics are the most appropriate for exploring these bivariate statistics.

According to Field (2013) Correlation coefficients, *r*, vary from 0 (no relationship) to 1 (perfect linear relationship) or -1 (perfect negative linear relationship). Cohen's standards were used to evaluate the correlation coefficient, where 0.10 to 0.29 represents a weak association between the two variables, 0.30 to 0.49 represents a moderate association, and 0.50 or larger represents a strong association (H. Chen, Cohen, & Chen, 2010; Cohen, 1988).

The scatterplots shown in Figure 5.8 suggest a positive correlation between degree of channelisation (lateral wander of vehicle positions) and both lane width and road width. The Pearson Correlation Coefficient, r was calculated to be 0.675 for the association between degree of channelisation and lane width and 0.650 for road width. *p*-values were found to be less than 0.001. The associations can be classified as a large and highly statistically significant.



(a)



(b)

Figure 5. 7 Scatterplot of the standard deviation of vehicle positions with (a) lane width, and (b) road width

In order to investigate how degree of channelisation (lateral wander of vehicle positions) differs based on the presence of different roadside features, boxplots of channelisation compared to the presence or otherwise of each road feature can be seen in Figure 5.9.

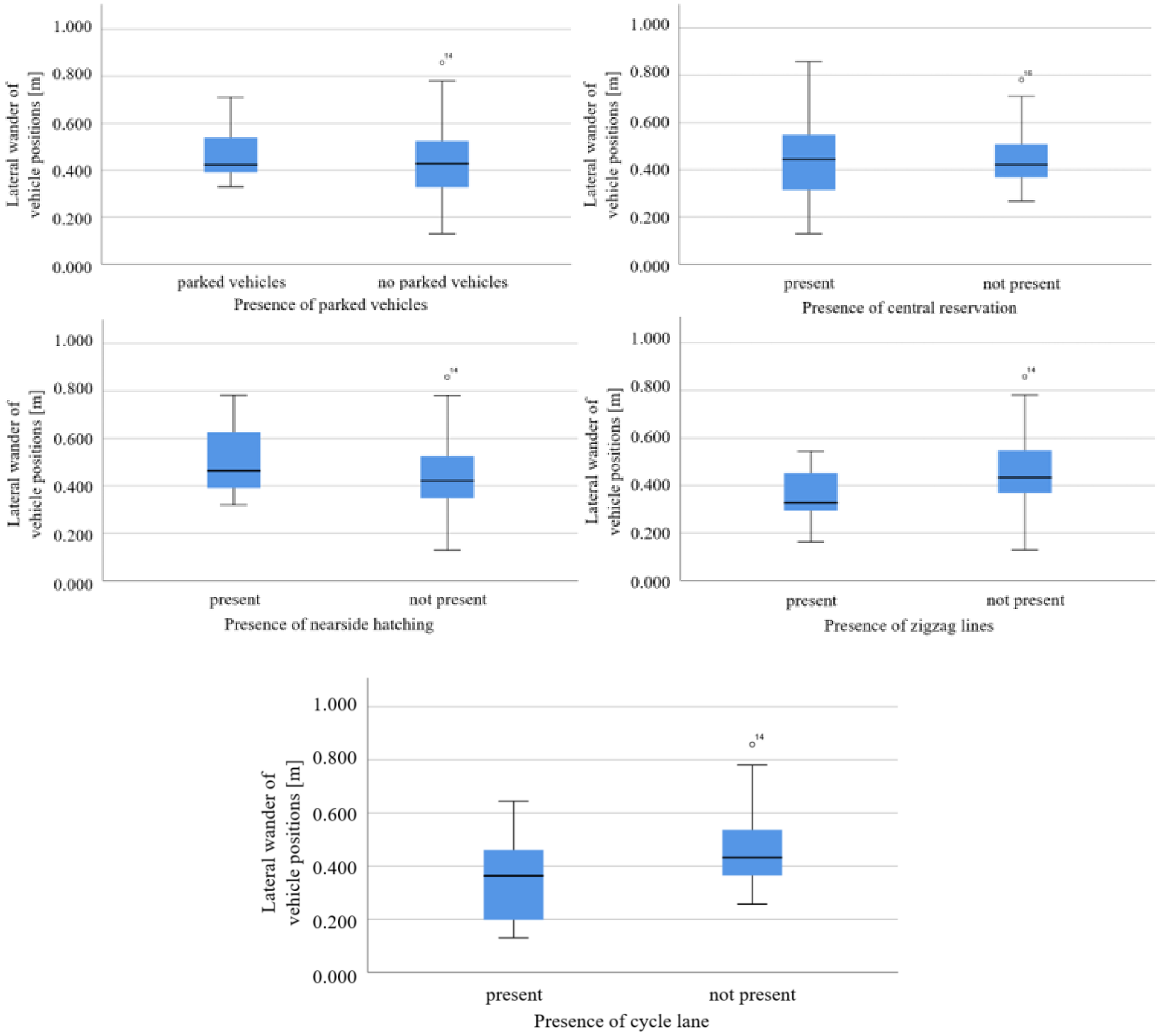


Figure 5. 8 Boxplot of the channelisation with presence of road features

From the boxplots presented in Figure 5.9, there are no obvious differences in the lateral wander of vehicle position and the presence or otherwise of any of the road features. This may indicate that there is no difference in the degree of channelisation based on the presence of roadside features. Independent samples T-tests were undertaken to test if there were statistically significant different mean levels of vehicle wander based on the presence of these roadside features. That is, whether a difference in the mean score of the degree of channelisation is apparent when particular road features are present or not. The results suggested that there is no statistically significant difference in the degree of channelisation for presence of parked vehicles (*p-value = 0.407)*, central reservation (*p-value = 0.793)* and nearside hatching (*p-*

value = 0.268). However, there is a significant difference for the presence of zigzag lines (*p-value = 0.021)* and for the presence of a cycle lane (*p-value = 0.013)*.

The Chi-square test of independence was performed to determine whether the explanatory road features are correlated or independent from one another. The results are presented in Table 5.5 below.

Table 5. 5 Chi-Square test of independence of categorical explanatory variables

		Pearson chi-square value	Asymptotic Significance (2-sided) (*p*-value)
1	Presence of parked vehicles vs Presence of central reservation	12.390	0.001
2	Presence of parked vehicles vs Presence of nearside hatching	5.297	0.014
3	Presence of parked vehicles vs Presence of zigzag lines	4.861	0.027
4	Presence of parked vehicles vs Presence of cycle lane	3.612	0.057
5	Presence of central reservation vs Presence of nearside hatching	0.617	0.432
6	Presence of central reservation vs Presence of zigzag lines	0.057	0.812
7	Presence of central reservation vs Presence of cycle lane	3.456	0.063
8	Presence of nearside hatching vs Presence of zigzag lines	0.015	0.903

9	Presence of nearside hatching vs Presence of cycle lane	0.297	0.586
10	Presence of zigzag lines vs Presence of cycle lane	2.711	0.100

From Table 5.5, it can be seen some explanatory variables may not be independent of each other (indicated by *p*-values of more than 0.05), whereas some are. This might be because some independent variables may not be entirely independent of each other as some of the road markings and other features are mutually exclusive. For instance, the presence of nearside hatching should not coincide with the presence of parked vehicles, as it is an offence to park on nearside hatched areas (Department for Trasnport, 2018).

5.2.6. Channelisation regression analysis

Regression analysis is widely used for understanding relationships between multiple variable and forming explanatory and predictive models (Montgomery, Peck, & Vining, 2012). More specifically, regression analysis helps understanding of how the typical value of the dependent variable changes when any of the independent variables is varied while other independent variables are fixed. In all cases, the estimation target is the function of the independent variables called the regression function. In regression analysis, it is also interesting to characterise the variation of the dependent variable around the regression function, which can be described by the probability distribution (Field, 2013).

When considering which type of regression analysis procedure to use, it is important to consider the kind of dependent variable to be included. The dependent variable of the standard deviation of vehicle lateral positions used in the analysis is recorded as a measurement on a continuous scale. In addition, the independent variables are more than one. Therefore, the type of regression analysis conducted was multi-variate linear regression to model the associations between channelisation and all factors and covariates. Multi-variate linear regression is used to develop a single equation from the set of independent variables (Sinharay, 2010).

The relationship between the dependent variable and the independent variable is also assumed to be linear (Alexopoulos, 2010). When constructing the model, it is necessary to specify a link function, which relates the combined explanatory variables and their coefficients to the dependent variable. There are many link functions possible, but based on the scatterplots shown in Figure 5.5, a unity link function was selected as it appeared that there were linear relationships between the dependent and independent variables.

In summary, the assumptions underpinning the regression analyses were: independence; linearity; normality; and homoscedasticity. In other words, the residual of a good model needs to be normally and randomly distributed (Alexopoulos, 2010).

A stepwise removal method was used to determine the best combination of all explanatory variables, both in terms of their main effects and all two-way interaction effects. Through this modelling, both in main effects and all two-way interaction terms, the road features (presence of parked vehicles, zig zag lines, cycle lanes, central reservation and nearside hatching) were found to be neither significant (at the 95% level) nor to have a large magnitude of effect. Moreover, they had little impact on the overall explanatory power of the model (adjusted-R^2 value). Therefore, the final model contains only two explanatory variables; road width and lane width, as seen in the following model outputs (Table 5.6).

Table 5. 6 Results (Magnitudes) of Multivariate Regression Analysis

Model	Multivariable analysis			
	Coefficient (β)	95% CI		p-value
		Lower	Upper	
Constant	-0.006	-0.104	0.092	0.902
Lane width [m]	0.033	0.018	0.047	1.40×10^{-5}
Road width [m]	0.017	0.008	0.026	2.65×10^{-4}

$$Y \text{ (standard deviation)} = -\,\mathit{0.006} + \mathit{0.033}X_1 \text{ (lane width)} + \mathit{0.017}X_2 \text{ (road width)} \qquad \textit{Eq. 2}$$

The regression analysis shows that both lane and road width are highly statistically significant (*p-values* < 0.001). The magnitudes of effect vary. For Lane Width (m), for every 1m wider the lane width, the lateral wander of vehicle position increases by 0.033m (95% confidence interval = 0.018m to 0.047m). To put this into context, the variation in Lane Width in the dataset was from a minimum of 3.40m to a maximum of 14.19m. Using the regression equation, this would equate to a difference in the degree of channelisation of 0.36m.

For Road Width, for every 1m wider the road, the lateral wander of the vehicle position increases by 0.017m (95% confidence interval 0.008m to 0.026m). Road width in the dataset ranged from a minimum of 5.50m to 22.7m. This range would relate to a difference in the degree of channelisation of 0.29m.

The overall model fit is expressed in terms of the adjusted-R^2 = 0.517 which is shown in scatterplot in Figure 5.10.

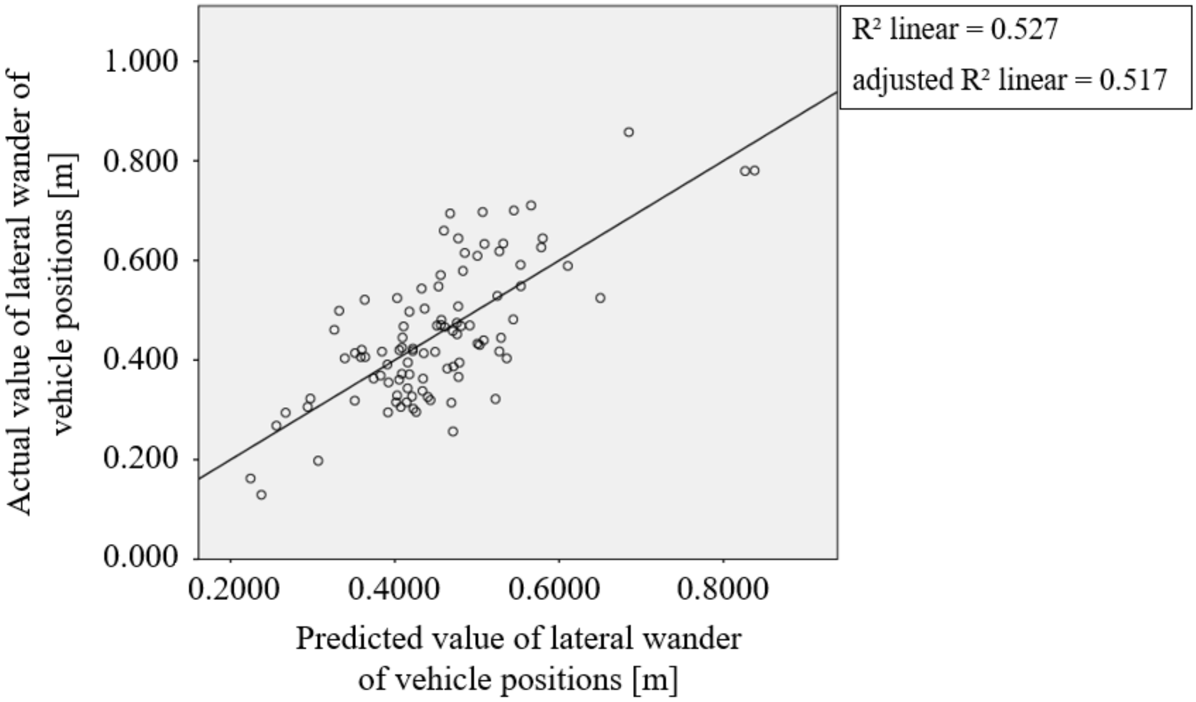


Figure 5. 9 Scatter plot of goodness of model fit

From the figure above, it was also shown that the distribution of residuals appears to be random and normally distributed from the predicted mean. The model output from SPSS is attached in Appendix E.

Considering the combined effects, the section with the narrowest combined lane and road width would be expected to have a lateral wander of vehicle position of 0.23m, and the widest combined lane and road width it would be 0.83m.

5.2.4. The Outliers in Data

Outliers are frequently encountered in observational data (Kwak & Kim, 2017). They are extreme/abnormalities that lie outside the overall pattern of distribution of a variable. Outliers may result from various factors, including some points in the sample simply being extreme, data being inappropriately scaled, errors on data entry, or unanticipated complexities may exist in the relationships between the variables (Field, 2013). It is essential to deal with outliers in the analysis of the data set by modifying or removing outliers where there is a clear reason for doing so, as they can drastically change the outcome of data analyses (Kwak & Kim, 2017).

There are different techniques to identify outliers. A simple method to explore outliers is through box plots. In the box plot shown in Figure 5.7, any data that lies outside the minimum or maximum lines is considered to be an outlier (Kwak & Kim, 2017). The lines are drawn based on the values of the median, lower quartile (Q_1) and upper quartile (Q_3) from the frequency distribution of the data. The difference between Q_1 and Q_3 ($Q_3 - Q_1$) is called 'interquartile range' (IQ).

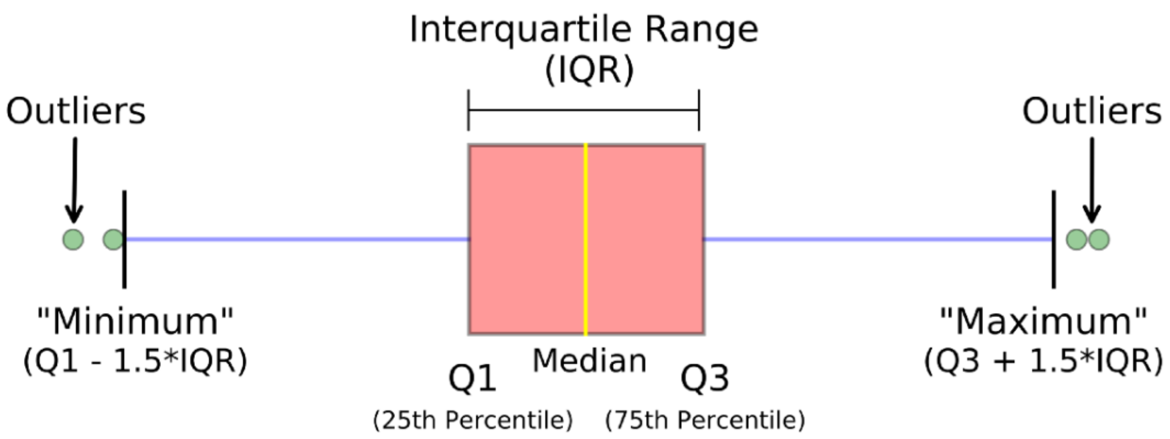


Figure 5. 10 Boxplot with outliers (Galarnyk, 2018)

When analysing data, these outlier observations may cause problem as they may strongly influence the results. Therefore, it is important to detect these outliers before undertaking statistical analyses.

Figure 5.9 shows the boxplots of channelisation with road features. It can clearly be identified that some road sections appear outside the fences of the boxplots. Road section number 55 on South Parade is one of the observations identified as an outlier. On reinspection of the data it appears as though this observation point was located slightly within a roundabout junction. Another outlier detected was road section number 75 on South Parade. This road section was also very close to a junction. Therefore, these two outliers related to sections that in hindsight were felt to be un-representative of usual highway sections and were removed from the original 100 observations. Section numbers 14 and 16 on Clarence Parade appeared to be outliers on the boxplot diagrams, however, after inspection, both of these observation points did not appear to be atypical of normal highway sections and hence, were not removed from the dataset.

5.3. Rutting and channelisation

Rutting is a common and significant form of pavement deterioration. To take into consideration the channelisation (lateral wander) of traffic and the effect of this on pavement rutting, further analysis was conducted as explained in following sections. To restate, the standard deviation of vehicle positions was used as the measure of the degree of channelisation/lateral wander of vehicle positions.

5.3.1. Rutting deterioration data

As mentioned in Chapter 4, the nearside rut depth for rutting deterioration data is considered for the analysis due to it being the critical rut on a road section. Figure 5.11 and Figure 5.12 illustrate the nearside and offside rut depth respectively. The mean of nearside rut depth is 1.810 mm whereas for the offside rut depth is 1.521 mm. The repetitive loading on the nearside wheel of a vehicle would be expected to cause greater rut depth compared to the offside wheel of a vehicle.

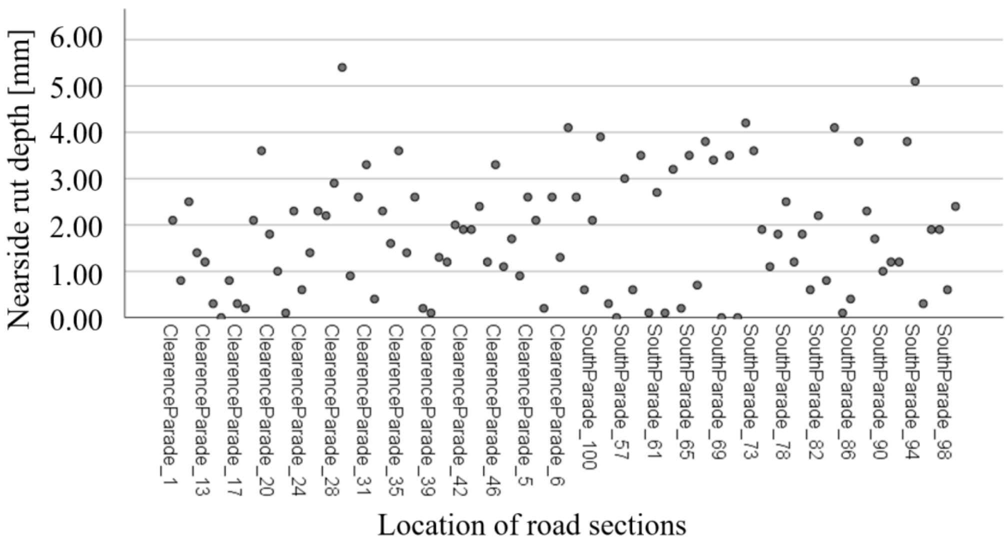


Figure 5. 11 Nearside rut depth data for road sections

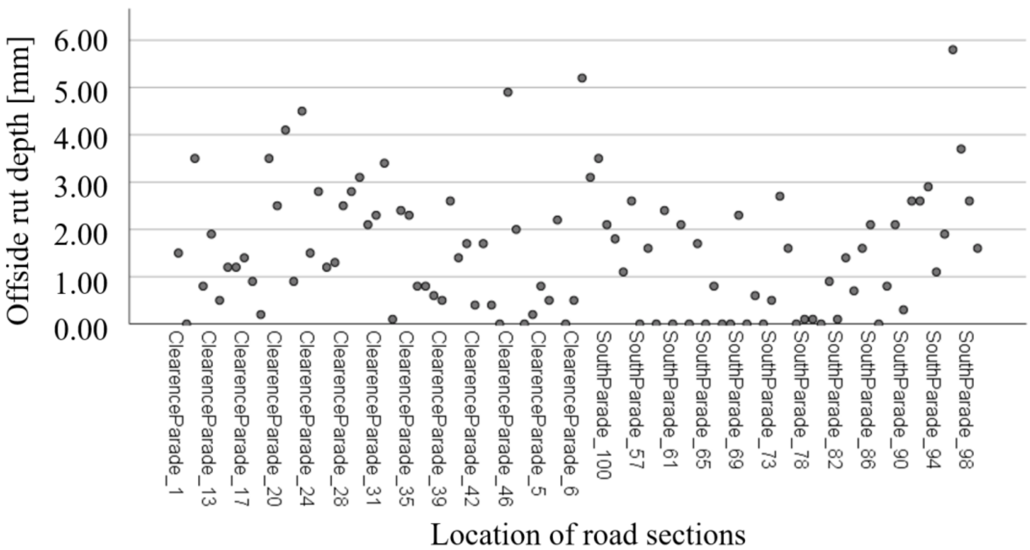


Figure 5. 12 Offside rut depth data for road sections

In Figure 5.13. the nearside rut depths for road sections are shown by year of measurement. The rut depths data were very consistent year to year except 2015 and 2016 years of data. For these two years, the data showed anomalous results with the pavement condition improving. Colas confirmed that no remedial work had been undertaken over that period, hence these years were disregarded. For the westbound lane, there was only one year of data (2018) that was available whereas for the eastbound lane, there were two years of data (2014 and 2017) available. For the eastbound lane, the nearest of the 2014 or 2017 data to the location of vehicle position data collection point was selected. I.e. for some point 2014 data were used and others 2017 data were used. There were minimal changes between the 2014 and 2017 years of data.

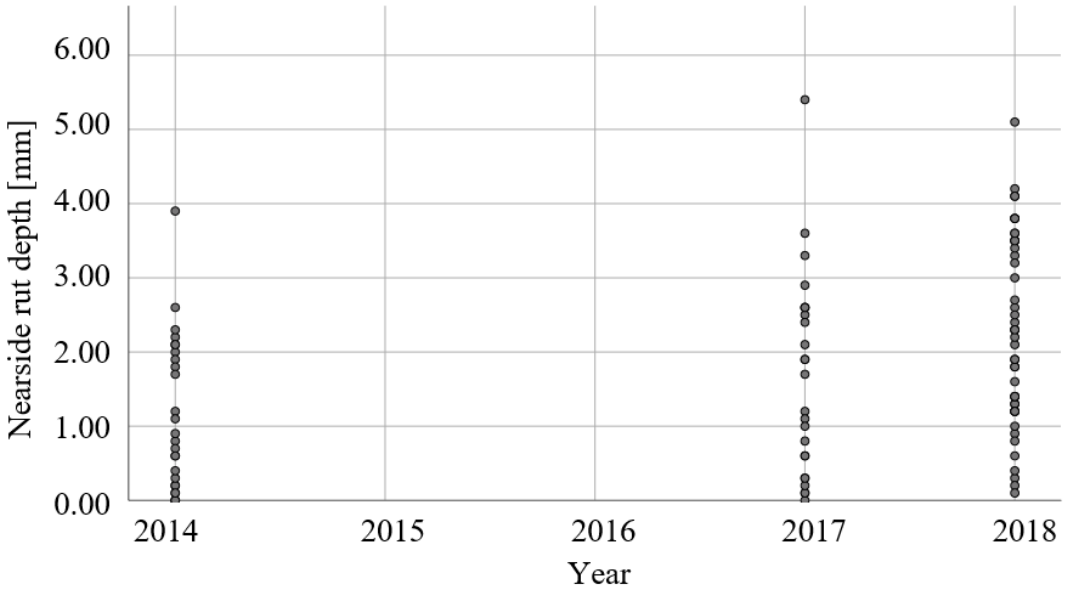


Figure 5. 13 Nearside rut depths for 2014, 2017 and 2018

Figure 5.14 shows the nearside rut depths recorded at each of the 98 locations used in this study.

Figure 5. 14 98 nearside rut depths used in the analyses

The rut depths were relatively small in most sections and so, in this case, are unlikely to have influenced driving behaviours as part of the feedback loop suggested in the literature by Aydin and Topal (2016).

5.3.2. Descriptive Statistics

The descriptive statistics were derived from SPSS for both scalable and nominal measures which are summarised in Table 5.7 and Table 5.8.

Table 5. 7 Descriptive statistics of scalable measures obtained in this study

Characteristics of variables	Minimum	Maximum	Mean	Std. Deviation
Lateral wander of vehicle positions [m]	0.1296	0.8577	0.4508	0.1367
Nearside wheel path rut depth [mm]	0	5.4000	1.8102	1.2970
Offside wheel path rut depth [mm]	0	5.8000	1.5214	1.3220
Curvature [m]	-373.3100	2000.0000	569.5230	747.3852
Pavement Camber [%]	-1.3000	6.4000	3.0827	1.5819
Annual Average Daily Traffic (AADT)	4602	4732	4663	65
Total number of cars *(Morning peak time)*	84	336	178	68
Total number of LGVs *(Morning peak time)*	7	26	14	5
Total number of HGVs *(Morning peak time)*	0	5	1	1
Number of buses/coaches *(Morning peak time)*	0	8	0	1
Total number of cars *(Evening peak time)*	105	276	183	63
Total number of LGVs *(Evening peak time)*	5	21	13	5
Total number of HGVs *(Evening peak time)*	0	3	1	1

Number of buses/coaches *(Evening peak time)*	0	8	0	1

Table 5. 8 Descriptive statistics of nominal measure obtained in this study

Direction of the lane		n
Lane		
	Eastbound lane	50
	Westbound lane	50

It should be noted that not all explanatory variables remained in the final regression modelling explained later in section 5.3.3.

The dependent variable and all independent variables were tested for normality. The dependent variable of nearside rut depth, is measured on a continuous scale and is normally distributed (Kolmogorov-Smirnov with Shapiro-Wilk normality tests p-values > 0.05). The frequency distribution of it is shown in Figure 5.15.

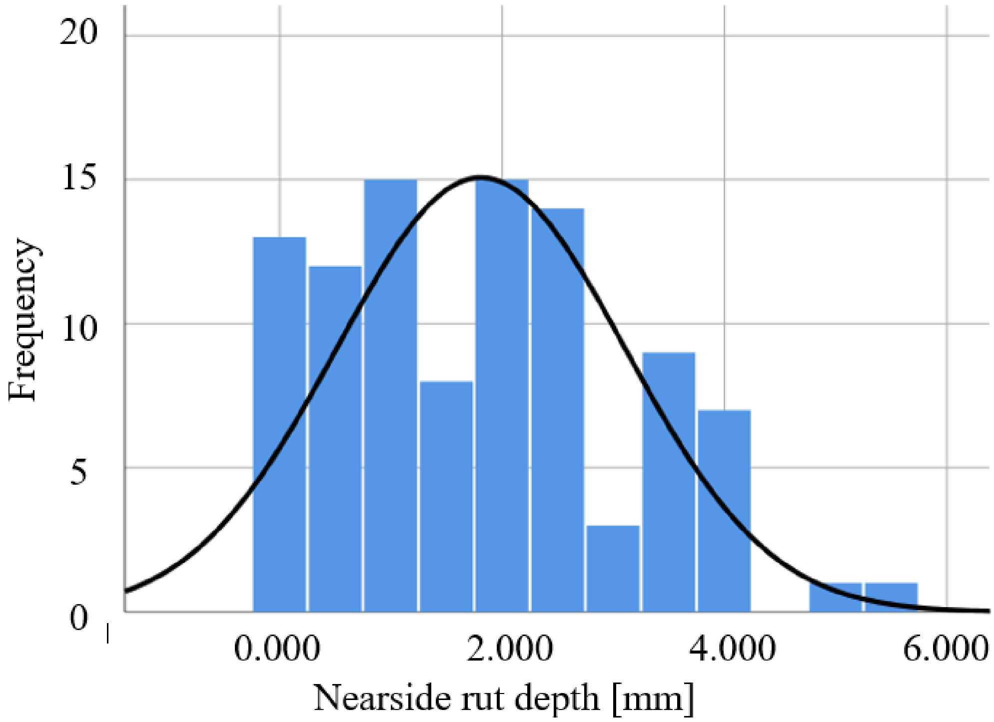


Figure 5. 15 Frequency distribution of nearside rut depth

One of the independent variables, pavement camber, was also tested for normality as shown Figure 5.16. It was found to be normally distributed.

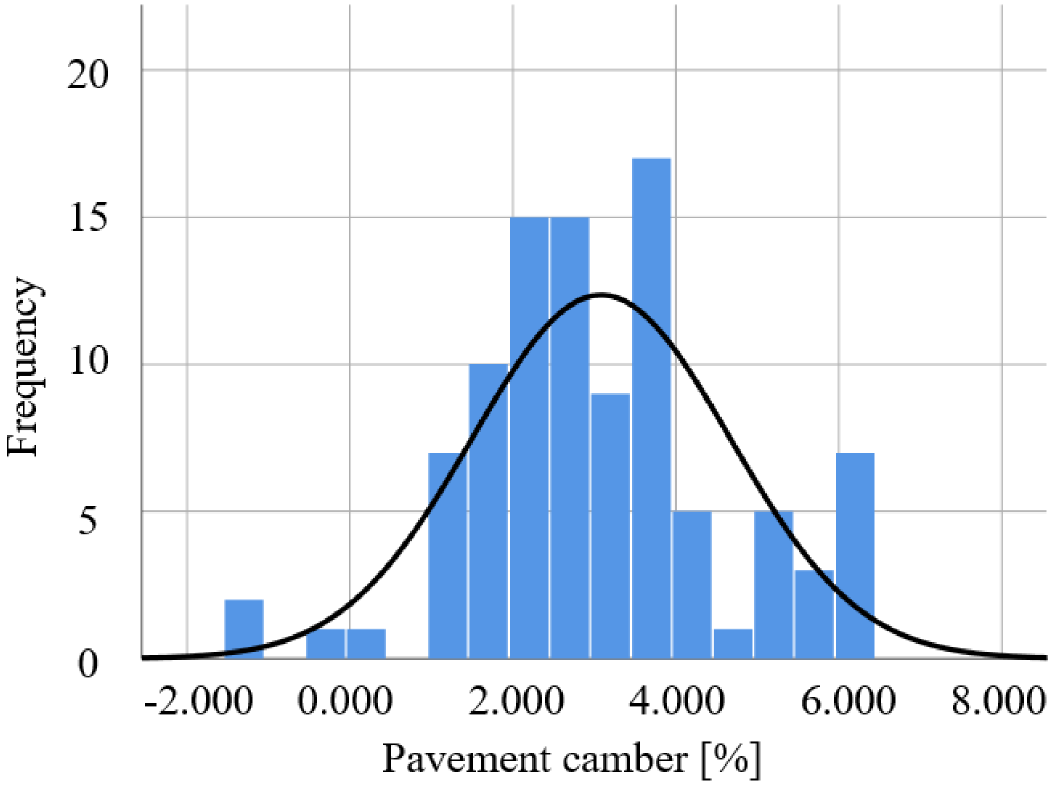


Figure 5. 16 Frequency distribution of pavement camber

In addition, the lateral wander of vehicle positions was tested for normality in section 5.2.3 and found to be normally distributed. The summary of test results is shown in Table 5.9.

Table 5. 9 Results of Kolmogorov-Smirnov and Shapiro-Wilk normality tests

Tests of Normality	**Nearside rut depth**	**Lateral wander of vehicle positions**	**Camber**
Kolmogorov-Smirnov (K-S) test	0.053	0.028	0.057
Shapiro-Wilk test	0.002	0.035	0.014

5.3.2. Correlation Tests of Variables

Parametric tests were conducted to find the Pearson correlation coefficients for the two-way correlations between variables. As the dependent variable, nearside rut depth, is measured on a continuous scale and is normally distributed (Kolmogorov-Smirnov with Shapiro-Wilk normality tests *p*-values > 0.05) the Pearson test was deemed to be suitable.

The scatterplot shown in Figure 5.17 indicates that there is a negative correlation between the nearside wheel path rut and the lateral wander of vehicle positions. The Pearson Correlation Coefficient was -0.223 (*p*-value < 0.05), indicating sections with lower the lateral wander of vehicle position (higher degree of channelisation or more channelised) tend to have increased rut depths.

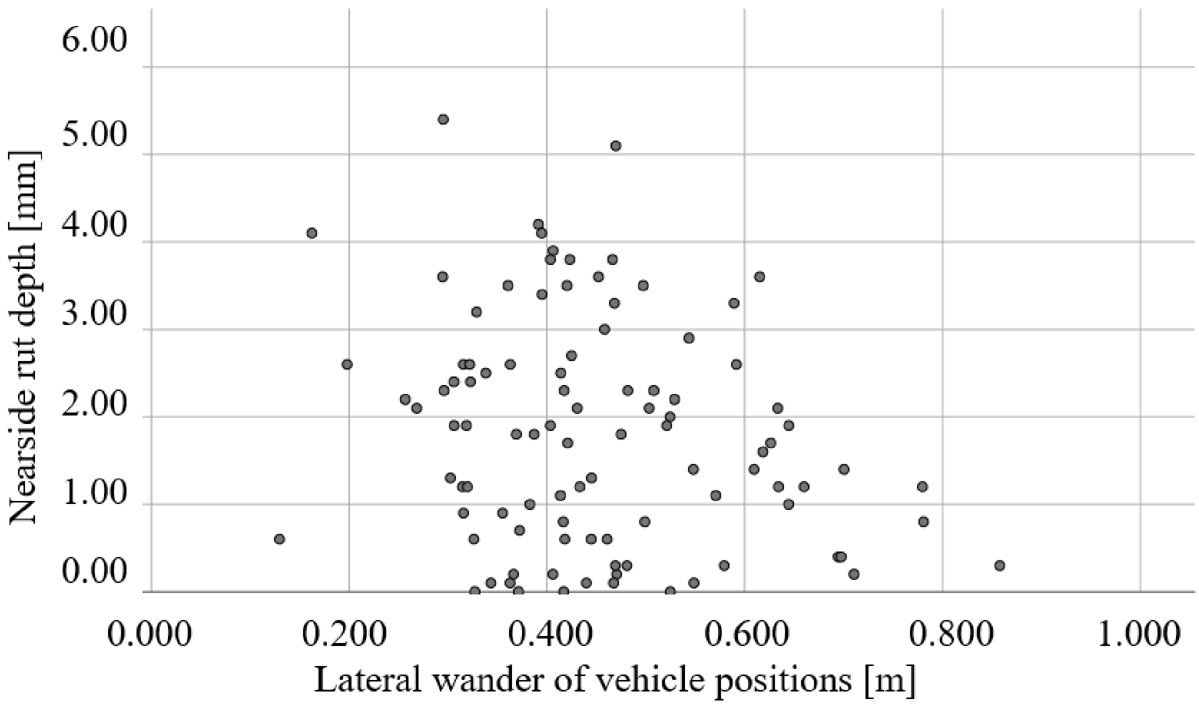


Figure 5. 17 Scatterplot of nearside rut depth with lateral wander of vehicle positions

Figure 5.18 represents the positive correlation between nearside rut depth and the camber of road on a scatter plot. The Pearson Correlation Coefficient was 0.112 (*p*-value >0.05), so it cannot be said with 95% confidence that the nearside rut depths relate to the camber of road.

However, it is close to being significant at the 90% confidence level and as such it was considered for inclusion in the subsequent regression analyses.

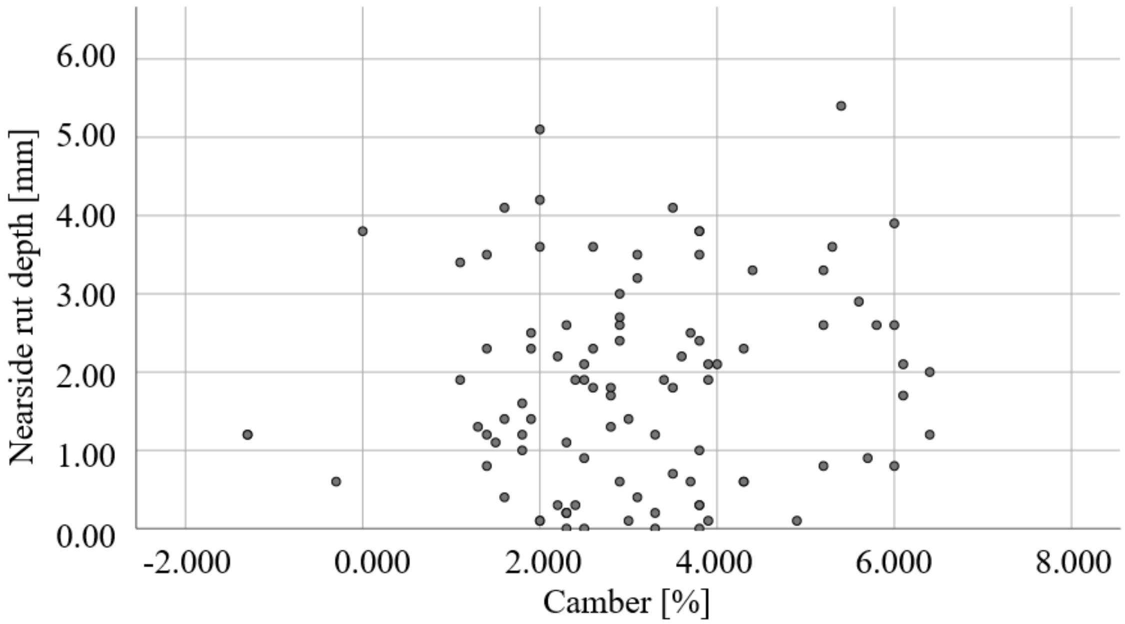


Figure 5. 18 Scatterplot of nearside rut depth with camber of the road

For new roads in the UK, cambers should be between 2.5% and 7%, or -2.5% and -7% (Highways Agency, 1993). However, on transition curves there may be small sections of pavements with cambers between -2.5% and +2.5%. The cambers analysed as part of this research were typically between +2% and +4%. Only two sections were on modestly super-elevated curves (indicted in Figure 5.16 as negative cambers).

A boxplot of nearside rut depth for the Eastbound and Westbound lanes can be seen in Figure 5.19. Independent samples T-tests were undertaken on the direction of the lane to estimate whether either the Eastbound or Westbound lane was associated with a difference in the degree of channelisation. The results suggested that there is a statistically significant effect on the rut depth for the direction of the lane (p-value < 0.05).

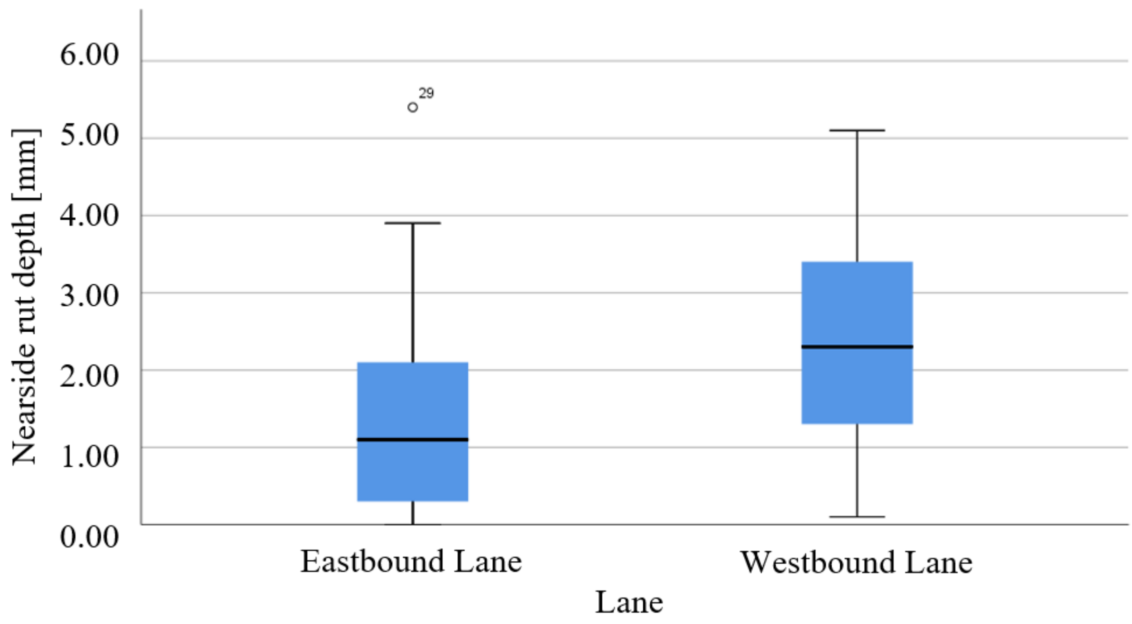


Figure 5. 19 Boxplot of the nearside rut depth with direction of traffic lane

No statistically significant bivariate correlations were found for the year of data collected, traffic levels, traffic composition, and horizontal curvature. It should be noted however, that due to the transport network in the case study area, there was little variation in traffic levels and composition along the length of the case study road.

5.3.3. Regression analysis

Multivariate linear regression analyses were performed to model associations between nearside wheel path rutting and all explanatory factors. The nearside rut depth at each of the 98 road sections was used as the dependent variable to represent the pavement performance. Table 5.10 shows the range of values for variables included in the final model.

Table 5. 10 Summary of descriptive statistics of variables used in the regression analysis

Characteristics of variables	Minimum	Maximum	Mean	Std. Deviation
Lateral wander of vehicle positions [m]	0.1296	0.8577	0.4508	0.1367
Pavement camber [m]	-1.3000	6.4000	3.0827	1.5819
Nearside rut depth [mm]	0	5.4000	1.8102	1.2970

The relationship between the dependent variable and the independent variable is also assumed to be linear (Alexopoulos, 2010). When constructing the model, it is possible to specify a link function, which relates the combined explanatory variables and their coefficients to the dependent variable. There are many link functions possible, but based on the scatterplots shown in Figure 5.17 and Figure 5.18, the unity link function was selected as it appeared that there were linear relationships between the dependent and independent variables.

The generalised linear model with a stepwise removal method was used to refine the model and only those variables that were found to be statistically significant were included in the final model specification. The unity link function and a normal distribution were used with degree of channelisation and camber of road entered as continuous variables and direction of lane entered as a categorical variable. Similarly, all two-way interaction effects were tested, but none were found to be statistically significant and were removed. The final model of nearside wheel path rutting is shown in the following equation and Table 5.11.

Nearside wheel path rutting = *-1.881* (degree of channelisation) + *0.396* (camber of road) + *1.633* (direction of lane) *Eq. 3*

Table 5. 11 Results of multivariate regression analysis

Model	Multivariate analysis Coefficient (β)	95% CI Lower	95% CI Upper	p-value
Constant	2.253	1.405	3.101	1.90×10^{-7}
Degree of channelisation [m]	-1.881	-3.432	-0.330	1.74×10^{-3}
Pavement camber [%]	0.396	0.230	0.563	3.00×10^{-6}
Direction of lane	1.633	1.110	2.157	9.90×10^{-10}

Figure 5.20 displays the predicted value of rutting at each of the 98 locations by the model with the actual rut depths measured. This gives an indication as to the overall model fit.

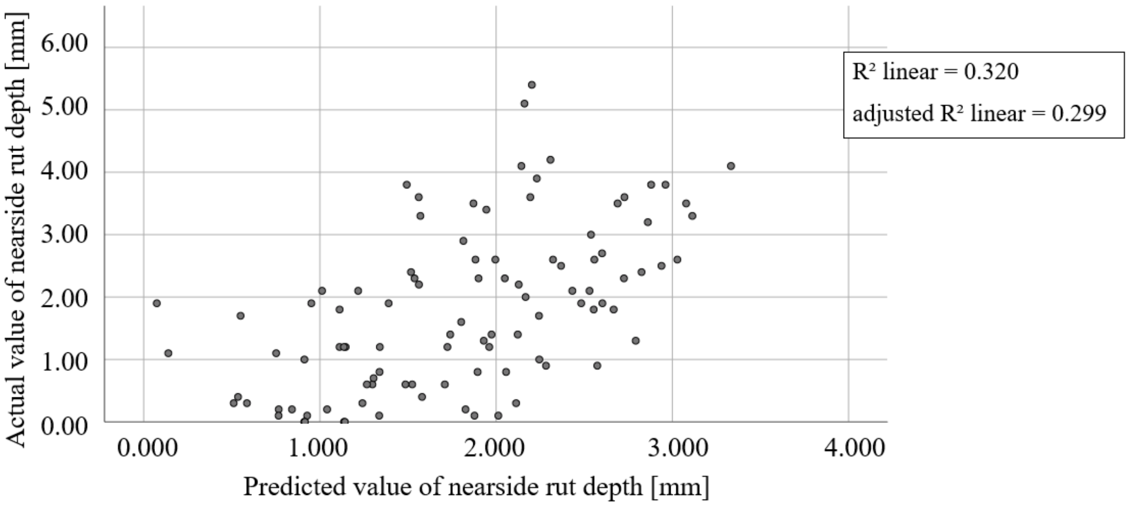


Figure 5. 20 Comparison of predicted and measured nearside wheel path rut depth

The explanatory power (adjusted-R^2 value) of the model was found to be 0.320, and adjusted R^2 was 0.299. As such, around 30% of the variation in rut depth could be explained by these three variables alone. The model output from SPSS is attached in Appendix E.

1 m difference in the degree of channelisation was related to 1.881 mm difference in rut depth. The degree of channelisation varied between the 98 locations and had a standard deviation of 0.137 m. This variation in the degree of channelisation was found to correspond to a difference in rut depths of 0.256 mm (1/5th of the standard deviation of the rut depths).

The direction of the traffic lane was statistically significantly associated with rut depth in the multivariate regression analyses. The westbound direction had on average a rut depth 1.633 mm more than eastbound traffic lanes all else being equal. AADT flows for east bound traffic and westbound traffic were also tested but were found to be neither statistically significant nor adding to the explanatory power of the model. As such they were removed from the final model presented here.

The year of data was included in the regression analysis however it was statistically insignificant; therefore, the final model did not involve the year of data variable within the regression equation.

5.4. Road Geometry and Rutting

The first part of the research involved analysing the impact of road geometry on the degree of channelisation. It was found that lane and road width are determining parameters for the lateral distribution of vehicles. During the second phase of the study, the association between the degree of channelisation and rutting were analysed. The results showed that the degree of channelisation has a significant and large impact on the rutting of pavements. The results were then combined to be able to produce a channelisation factor in terms of road geometry parameters for pavement engineers to modify pavement thicknesses more appropriately when designing a new asphalt pavement. As opposed to current guidance (Walsh et al., 2011b) to simply double the load and thickness when channelisation is expected, this new approach aimed to estimate the effects of channelisation based on the geometries of the road.

To be able to translate the degree of channelisation in practise into a design load, the approach adopted was to combine the two predictive equations developed from the regression analyses. The combined equation is presented below.

Nearside wheel path rutting = *-1.881* (- *0.006* + *0.033* (lane width) + *0.017* (road width)) + *0.396* (camber of road) + *1.633* (direction of lane) *Eq. 4*

This can be simplified as follows:

Nearside wheel path rutting = *0.0112 – 0.0620* (lane width) - *0.0320* (road width) + *0.396* (camber of road) + *1.633* (direction of lane) *Eq. 5*

From the equation above and based on the data set used, it can be seen that 1 standard deviation difference in lane width (1.82 m, as presented in Table 5.2) resulted in 0.113 mm difference in nearside rut depth. Similarly, 1 standard deviation difference in road width (2.92 m, as presented in Table 5.2) resulted in 0.093 mm difference in nearside rut depth. To put this into context, the variation in lane width in the dataset was from a minimum of 3.40 m to a maximum of 14.19 m. Using the combined model output, this would equate to a difference in nearside rut depth of 0.67 mm. Road width in the dataset ranged from a minimum of 5.50m to 22.7m. This range would relate to a difference in the nearside rut depth of 0.55 mm. Considering the combined effect of both lane and road width, this corresponds to a difference in nearside rut depth of 1.22 mm which was approximately the same with the standard deviation of the nearside rut depth data used.

Figure 5.21 and Figure 5.22 shows the graphical representation of the impact of lane and road width on nearside rut depth. This can be summarised as 1 standard deviation decrease in lane width contributes 8.7% and in road width contributes 7.1% to increase in nearside rut depths.

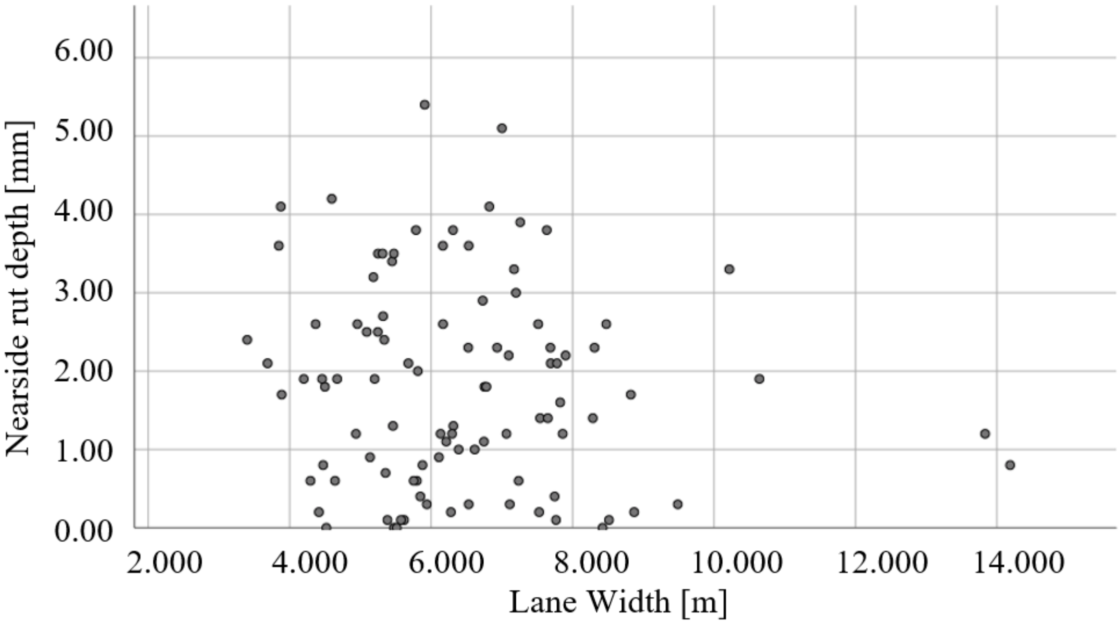


Figure 5. 21 Scatterplot of nearside rut depth with lane width

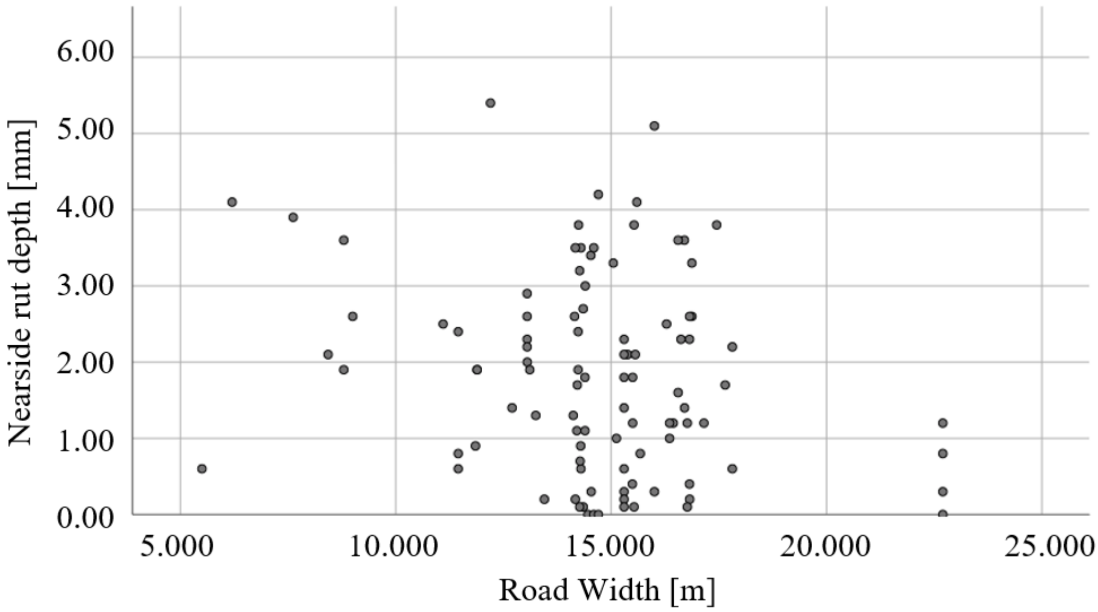


Figure 5. 22 Scatterplot of nearside rut depth with road width

It is important to determine a correct channelisation factor based on the degree of channelisation as use of a binary value of 1 or 2 can lead to considerable differences in the asphalt pavement thickness design methods. The results here suggest the factor be based on the lane width the road width.

Finally, Figure 5.23 summarises the goodness fit of final model built from combining the two equations. The overall model fit is adjusted-$R^2 = 0.273$ That is 28% of the variation in rut depth can be explained by the variations in the explanatory variables.

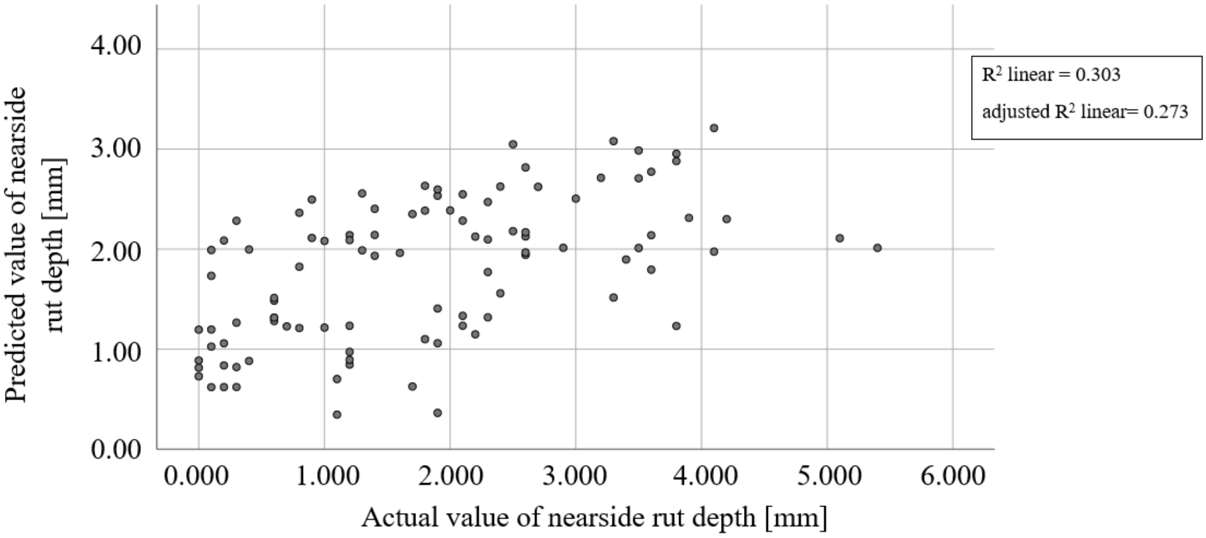


Figure 5. 23 Scatterplot of goodness of combined model fit

The assumption of residuals being normally distributed is presented in Figure 5.24. The Pearson correlation test was run to check whether there was any correlation between residuals and other explanatory variables such as vehicle composition, presence of roadside features, curvature and camber of road. Although bivariate comparisons of the residuals and some of these explanatory variables showed some correlation, when these explanatory variables were entered into the regression analysis, they were not found to be statistically insignificant and did not add to the explanatory power of the model, hence they were not included. This may be due to correlation with other explanatory variables that were included in the model. To clarify, the residuals did not correlate with any of the explanatory variables contained within the final regression equations.

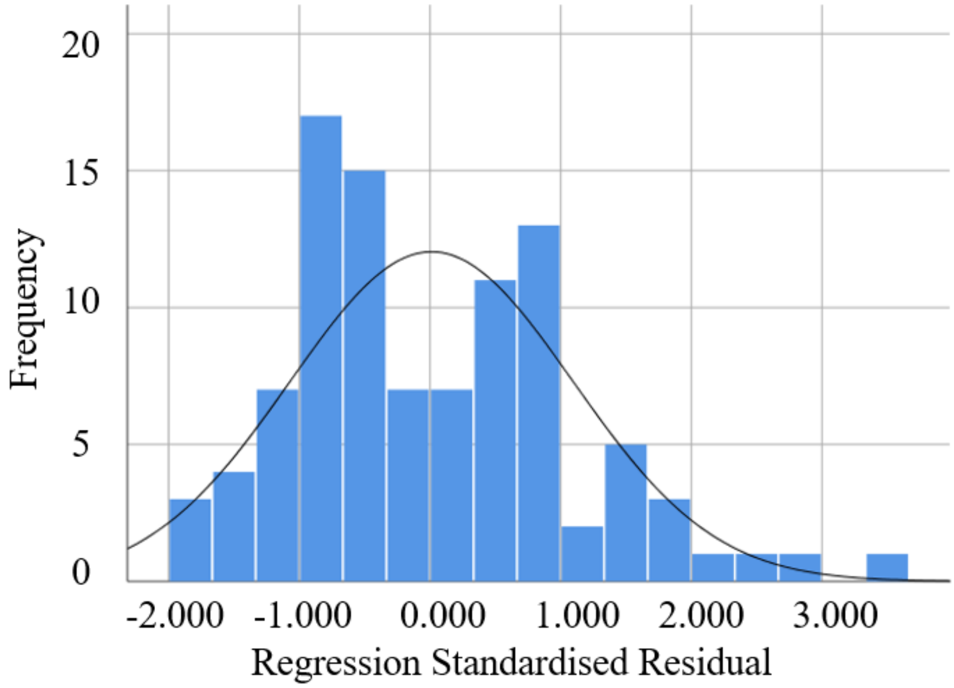


Figure 5. 24 Frequency distribution of residuals for the final model

Figure 5.25 plots rut depths data predicted by the combined model against actual rut depths data. Values above the 45- degree line are overestimated by the model, while values below that line are underestimated. The 45- degree line also explains how good the model is at predicting the rut depths. The standard deviation of residuals is 1.08 mm with a R-squared value of 0.32. To compare the standard deviation of residuals value of 1.0826 mm to the standard deviation of the actual observed rut depth value of 1.2970 mm.

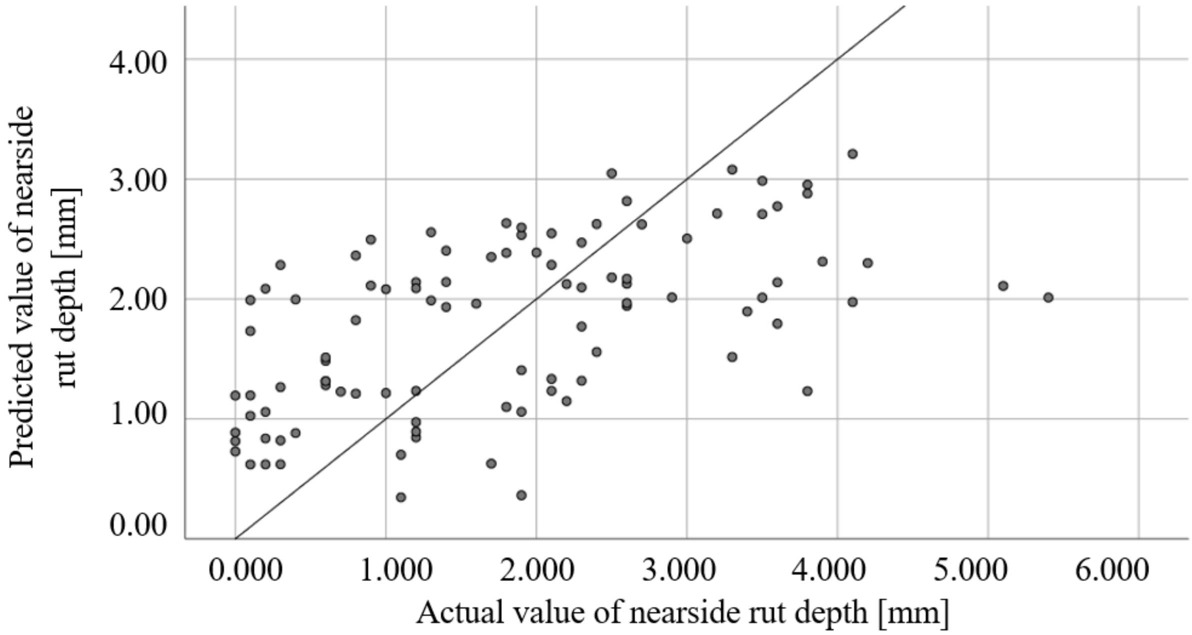


Figure 5. 25 Linear regression combined model 45°-degree plot

5.5. Chapter Summary

This chapter presented the impact of road dimensions and presence of road features on the degree of channelisation. Further analysis indicates that the difference in channelisation relates to different rut depths forming on an otherwise consistent asphalt pavement. Furthermore, to account for channelisation successfully, it is suggested to consider the issue as a degree rather than a binary value in pavement design.

Chapter 6 Discussions, Conclusions and Recommendations

6.1. Introduction

This chapter discusses the findings, interprets their meaning and presents the final conclusions. The interpretation of findings with reference to the research objectives are presented, then the contribution to knowledge is explained, followed by the limitations of the research and recommendations for further study.

6.2. Interpretation of Findings

The principal aim of this study was to investigate the effect of channelisation on the rutting performance of asphalt pavements so that highway engineers can make better-informed decisions regarding pavement design and management. A set of objectives was established to achieve the main aim, each objective was accomplished using different methods in this project. The process of delivering those objectives is described below:

Objective I: Determine the relationship between channelisation and road geometry.

The first objective of this study focused on investigating the impact of road dimensions and presence of road features on the degree of channelisation/lateral wander.

A multiple linear regression was calculated to predict the degree of channelisation (standard deviation of vehicle position) based on road geometry and roadside features. Both lane width and road width were found to be significant predictors of degree of channelisation. A statistically significant regression equation was calculated with an adjusted R^2 value of 0.517. Based on the derived useful interfaces from the overall model and the estimated values of the parameters, the adjusted-R^2 value of 52% can be evaluated as large value. It means 52% of the variation in the degree of channelisation can be explained by the model whereas 48% of the variation is due to unobserved characteristics such as weather conditions, road surface conditions, drivers' behaviour etc. The final regression equation equal to:

$$\text{Y (standard deviation)} = -\ 0.006 + 0.033X_1 \text{ (lane width)} + 0.017X_2 \text{ (road width)} \qquad \textit{Eq. 6}$$

Where both lane width and road width measured as metres. The lateral wander of vehicle positions increased 0.033 metres for every 1 metre wider lane width and 0.017 metres increased for every 1 metre wider road width. The association between lane width and road width suggested a positive correlation based on Pearson Correlation Coefficient with a p-value < .001. (wider road sections correlated with wider lane widths). Although these two independent variables were not entirely independent of each other, each of them was found to have a statistically significant effect over and above the effect of the other one. In that case, it is important to consider their effect as a combined effect. Although it may be possible to undertake some sort of cluster analysis or principle component analysis that could untangle the lack of independence in these two variables, such analysis would create abstract variables that would be of little use to highway engineers in predicted the performance of pavements. It is noted though in section 5.4 that the pavement engineers ought to consider both the road width and lane width together rather than relying on only one or the other when using the final model output.

Considering combined effects, the section with the narrowest combined lane and road width would be expected to have a lateral wander of vehicle position of 0.23 metres and the widest combined lane and road width, it would be 0.83 metres. It is important to have the data to support whether or not the relationship remains linear beyond the ranges that the data was collected for. Theoretically, the relationship is not possible to remain linear at extremely narrow widths of lane and road. When the traffic is perfectly channelised at a certain narrow lane width, even if the lane width gets narrower the traffic cannot be more channelised as it is not possible to have a negative lateral wander of vehicle position. Therefore, it is plausible that the relationship is not linear at extremely narrow sections. The ranges of lane width covered in this research are fairly typical with the lane width expected on UK's highways (3.65 metres).

However, it might not be possible to extrapolate the results to cover some extreme cases such as sections where there is a toll booth or bus stop. Regardless of this, the results may be replicable on the majority pavement sections in the UK. The regression equation found in this research therefore, can be used in some different scenarios, but it is important to be cautious for scenarios that have not been tested in this research.

The relationship considered in the current state of research in the UK was based on a binary judgement as shown in Figure 6.1 (Garrett, 1983). However, the research described in this thesis indicates that the relationship is linear, based on lane and road widths, rather than being binary, therefore the distribution of vehicle positions should not be categorised as either channelised or unchannelised as in the current design guidance (Walsh et al., 2011a).

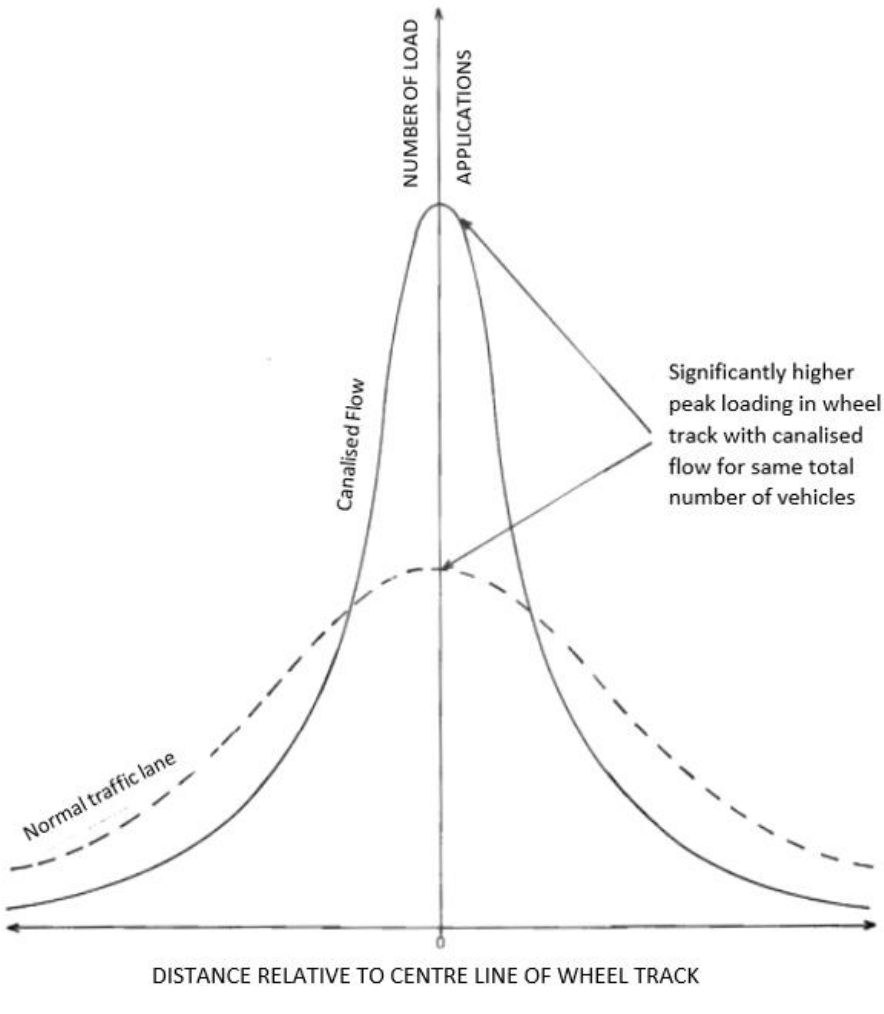


Figure 6. 1 Effect of canalised traffic flow on peak damaging power (Garrett, 1983)

The presence or otherwise of any road feature was not found to be related to the degree of channelisation, but both lane width and road width were statistically significantly related to the vehicle wander. Although none of the road features was found to be significantly associated with the degree of channelisation/lateral wander, it may be the case that this was due to the relatively small number of sites that contained particular road features. For example, 24 road sections contained parked vehicles, 34 of them had a central reservation, 16 of them were with nearside hatching, 13 of them were with zigzag lines and only 10 of them were with a cycle lane. Logically, these road features combined account for any difference between lane width and road width which was found to be statistically significant. Also, the road features were described in binary terms: present or not present.

It is plausible that if the road features had been considered as scalable measurements of their cross-sectional width, then they may have been statistically significant. The reason for such a supposition is that the road width was measured from one kerb to the other, the lane width from the nearside to offside lane markings, and the difference between the two measurements was made up by the widths of any road features. Therefore, the difference between the road and lane width negates the need to consider the presence or otherwise of any road feature. For example, on a section of road with a cycle lane and a central reservation, the road width might be 11m and the lane widths 4m each. The 3m difference between the combined widths of the lanes and the width of the road would relate to the two 1m wide cycle lanes at either side of the road and 1m wide of central reservation in the middle of the road. As such, the presence of any particular road feature in itself does not appear to be significant but the combined width of all road features present does. Figure 6.2 shows a section of the case study highway with a cycle lane and central reservation. The presence of the road features causes there to be a large difference in the width of the road compared to the width of the lanes.

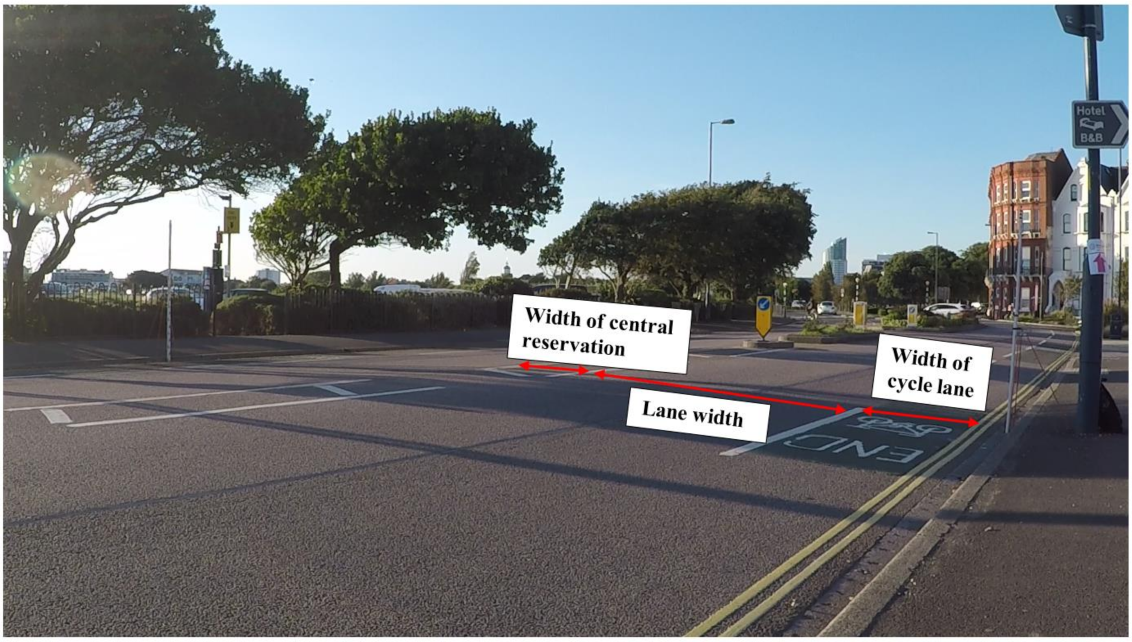


Figure 6. 2 Road section with presence of cycle lane and central reservation

Whilst it may be interesting to rerun the analyses with road features considered as scalable measurements, the results that this might produce are likely to be less helpful to highway engineers. The current results enable a highway engineer to take just two dimensions (road and lane width) to estimate the degree of channelisation. If the individual roadside features were found to be significant as scalable measurements, highway engineers would need to take many more measurements to estimate the standard deviation of wheel positions as opposed to just two measurements. Further work could consider widths of features but the results presented here remain both statistically robust and also practically useful.

It is suggested here that drivers do alter their lateral position as a result of features outside of their traffic lane and do so depending only on the width of these features. For example, when there is the presence of a cycle lane on the side of the road, it might have been expected that the drivers drive even closer to the centre of the road to get further away from the cycle lane. It does not appear that this is the case based on the results presented here. The results of this study indicate that two sections of road with identical lane widths, but where one section has a cycle lane present (causing a wider road width), vehicles are actually spread more widely across the pavement section. It appears as though drivers perhaps consider both the width of their traffic lane but also the distance to the nearside kerb. Hence, the results in this study showed that there seems to be an effect of the cycle lane on narrowing the lane width only. It is not that the drivers drive further away from the left side of the road to try to avoid the cyclists. The situation is also the same with presence of parked vehicles. Similarly, it might have been expected that drivers would drive further away from the nearside edge of the traffic lane when there is a parked vehicle due to concerns over the doors of those parked cars being opened into the traffic lane. However, the findings of this research suggest that the width of the parked vehicle area seems to have no such effect. In summary there seems to be no effect of road features over and above their effect of narrowing the lane widths compared to the road width.

These findings partially support international standards that use lane width as a proxy for the degree of channelisation (Dutch, Austrian & German) rather than the current binary measures used in UK guidance (Walsh et al., 2011a). In the Dutch design standards presented by Atkinson et al. (2006), the lane width is considered to have a linear relationship with the damage caused by the traffic, however, it is not clearly mentioned how the distribution of the loads was evaluated in comparison to lane width. The German standards explained by Sieber (2012) and Austrian standards presented by Blab and Litzka (1995) suggest that channelisation can be determined based on lane width, measured on a scale, up to a maximum lane width of 4.25 metres. The magnitudes of the effect vary. All the design guidance reviewed only use lane width, whereas, in this research, road width was found to be a significant contributor to lateral wander of vehicle position in addition to lane width. This new finding contributes to the knowledge on the causes of traffic channelisation/lateral wander of vehicle positions.

Objective II: Investigate the impact of channelisation on asphalt pavement rutting.

The first objective of this study showed that lane and road widths relate to the degree of channelisation. However, there is little in the way of guidance in the UK as to when traffic might be expected to be channelised and the doubling of the traffic load when this is expected is based on little empirical evidence. Therefore, within the scope of this objective, the study focused on giving further guidance as to the damaging effect of channelisation/traffic wander on rutting on flexible pavements in the UK. The results indicated that the difference in channelisation observed in this study relates to different rut depths forming on an otherwise consistent asphalt pavement.

With multivariate linear regression analyses, the rut depth can be predicted from the degree of channelisation, camber of road and direction of lane by the following formula:

Nearside wheel path rutting = *-1.881* (degree of channelisation) + *0.396* (camber of road) + *1.633* (direction of lane) *Eq. 7*

Where the degree of channelisation is measured as metres, the camber of road measured as a percentage and the direction of lane recorded as a category of being either on Eastbound or Westbound. The overall model fit was calculated to be an adjusted-R^2 value of 0.299. As such, around 30% of the variation in rut depth could be explained by these three variables alone whereas 70% of variation is due to the unobserved variables such as the construction of the pavement, changes in traffic levels over time, small changes to underlying soil conditions and quality/consistency of the construction of the pavement. The results show a moderately large magnitude of effect between the degree of channelisation and rut depth based on the case study location and data. 1 m difference in the degree of channelisation was related to 1.881 mm difference in rut depth. The degree of channelisation varied between the 98 locations and had a standard deviation of 0.137 m. This variation in the degree of channelisation (SD) was found to correspond to a difference in rut depths of 0.256 mm (1/5th of the standard deviation of the rut depths).

For road camber, every 1 % greater the cross-fall, the nearside wheel path rutting was 0.396 mm greater. The standard deviation in road camber observed resulted in 0.198 mm difference in rut depths.

The direction of the traffic lane was statistically significantly associated with rut depth in the multivariate regression analyses. The westbound direction had on average a rut depth 1.633 mm more than eastbound traffic lanes all else being equal. The reason for this variable to be significant in the overall model might be related to unobserved variables associated with the different traffic lanes, such as the detail of the pavement construction, thicknesses, compaction levels etc. The variable is specific only to the case study location, but has been included in the final model as an important control for these unobserved factors.

The results presented here supports the studies conducted by Erlingsson et al. (2012) and Harvey et al. (2000), as the rutting accumulates with the level of lateral wander of vehicle positions. The results obtained in this study contradict the advice provided in the UK (Walsh et al., 2011b) as they indicate a linear relationship between channelisation and rutting, as opposed to a binary one. Figure 6.3 shows the 98 survey locations, colour coded to indicate the deepest ruts (red) to shallowest ruts (yellow). The widest and narrowest road/lane sections are detailed.

Figure 6. 3 Illustrated map of the degree of channelisation for narrowest and widest road sections with rut depths

These findings could, therefore, enable more accurate estimations of the design lives of pavements to be made, and/or for pavements to be better designed and maintained to meet specified lifespans.

The results presented here may enable pavement engineers to modify pavement thicknesses more appropriately, as opposed to simply doubling the load and thickness when channelisation is expected based on the standard deviation of vehicle positions.

Objective III: Suggest ways in which current pavement design guidance and Pavement Management Systems (PMSs) could be enhanced to better account for channelisation in the future.

Objective I and Objective II were combined to suggest ways of considering road geometry to produce a channelisation factor to be incorporated into the calculation of design load and pavement design. In order to reflect the degree of channelisation in practise in the design load, the approach adopted was to combine the two predictive equations developed from regression analyses as shown below.

Nearside wheel path rutting = *0.0112 – 0.0620* (lane width) - *0.0320* (road width) + *0.396* (camber of road) + *1.633* (direction of lane) *Eq. 8*

Where both the lane and road width were recorded in metres, the camber of road was measured as a percentage and the direction of lane was recorded as category of being either Eastbound or Westbound. This final model, combined with the information provided by the first regression output into the second regression output, allows pavement engineers to predict the future rut depth on an existing road for any value of the standard deviation of the vehicle position. From statistical point of view, when the regression analysis was rerun including all independent variables individually, the results were similar with the combined model due to the residuals of the two regression equations being normally distributed. Therefore, combining the two regression equations was thought to be the best way of modelling the rut depths depending on all other independent variables.

The combined model suggested that 1 standard deviation difference in lane width would relate to 0.113 mm difference in nearside rut depth and 1 standard deviation difference in road width would result in 0.093 mm difference. The variation gained both in lane width (minimum of 3.40 m to a maximum of 14.19 m) and road width (minimum of 5.50 m to 22.7 m) would relate to a difference in nearside rut depth of 1.22 mm which was approximately the same with the standard deviation of the nearside rut depth data measured by COLAS.

The final model, combined with the information provided by the first regression output into the second regression output, allows pavement engineers to predict the future rut depth on an existing road for any value of the standard deviation of the vehicle position. That is, where pavement engineers are working on an existing road and they need to predict future deterioration of the existing road, pavement engineers can measure the standard deviation of the wheel positions as set in this thesis and use this directly in equation 2. It is useful therefore to have both equations expressed independently as well as in a combined format. Statistically, the risk of combining the two equations in this way stems from non-normal residuals in either equation or from a lack of independence of the explanatory variables in the newly combined equation. Although the analysis of residuals in the thesis should provide reassurance that there is no such issue, an alternative way of creating the combined final model to specify an alternative to creating the combined final model was to undertaken further regression analyses to estimate the parameters and the intercept which is presented in Appendix E. This alternative has been performed and produced results weaker than the second model because the model did not include measured standard deviation. It included an estimate instead. However, there were unobserved factors that explain the variation in standard deviation. By using estimates of standard deviation (lane width and road width) and by combining the two models or by developing a new equation from new regression analysis, the unobserved characteristics that contribute to the standard deviation were not covered. It is suggested that highway engineers should measure the standard deviations (working on a maintenance scheme or predicting lifespan of an existing road). For a new road, the standard deviation can be estimated from the lane width and road width, however this will give a less certain estimate of the nearside rut depth than if they are measured the standard deviation.

The method of calculating the design traffic load in the UK does not include lane width. Atkinson et al. (2006) stated that the typical lane width on new trunk roads and motorways is 3.65 metres explained in (Highways Agency, 2020) and there is a little variation in this. However, this research found that even if the lane width was stated to be limited to 3.65 metres, there was a considerable range of lane widths captured in data collection on primary road networks. The results of this research showed that 1 standard deviation decrease in lane width contributes 8.7% increase in rut depths.

The coefficients found in the final equation can be used to multiply up the design traffic load to account for channelisation of traffic. The current design methodology suggests to double the traffic load when the channelisation is expected based on a study conducted by Kent County Council (Garrett, 1983). However, there is no guidance as to when to consider the traffic to be channelised or unchannelised. It is important to assess a correct channelisation factor based on the degree of channelisation. From this research it was found that the degree of channelisation varied based on lane width and road width. As such, the combined model relates pavement deterioration (rutting) to the geometry of road to consider in determining appropriate pavement thicknesses. The model demonstrated an alternative perspective to deal with the channelisation factor would be to multiply the design traffic by 0.0620 times the lane width and also to multiply the design traffic by 0.0320 time the road width road width. To put this into context, the expected nearside rut depth was calculated using typical lane and road width in the UK using the final predictive equation developed here. The lane width being 3.65 metres and road width 7.3 metres. Also, the typical road camber of 2.5% was taken. The lane direction factor was considered as the average of 0.5 (1 for Eastbound lane and 2 for Westbound lane). The calculation is as follow:

$$\text{Nearside wheel path rutting} = \mathit{0.0112} - \mathit{0.0620}\,(3.65) - \mathit{0.0320}\,(7.3) + \mathit{0.396}\,(2.5) + (\mathit{1.633}/2)$$

$$= 1.3578 \text{ mm} \qquad \text{Eq. 9}$$

The lane width was then reduced by 1 metre and calculated the nearside rut depth to be 1.4198 mm. This means that for 1 metre difference in lane width there would be a 4.6 % difference in the nearside rut depth. Similarly, for road width, 1 metre reduced road width resulted in a 2.4%

difference in nearside rut depth. In order to account for this, the suggestion would be to increase or decrease (as appropriate) the design traffic by the same percentage.

As the channelisation in this research was not considered as binary relationship, the factor obtained for channelisation was a number multiplied by the lane width and a number multiplied by the road width. For most single, two-lane carriageways, 1 metre difference in the lane width would equate a 2 metres difference in road width, if there are no roadside features present (i.e. where the road width is exactly made up of the two-lane widths). Every 1 metre narrower the lane width would equate 2 metres narrower roads; therefore, the design traffic needs to be increased by 9.4 % (4.6% due to the narrower lane width and 2x2.4% due to the narrower road width).

These findings were compared to international design standards that use lane width to account for channelisation in the design load. In the Austrian design standards, presented by Blab and Litzka (1995), 1 metre increased lane width results in 18% drop in design load which is greater than the 9.4% indicated by this study. The German Design standards suggests that for wide lanes, the magnitude of the effect of a 1m change in width is more modest, although still slightly above the results presented in this study. However, for narrow lanes the magnitude of effect of a change in width is greater. That is, the relationship implicit in the German standards is non-linear with a large effect at extremely narrow road sections. Unfortunately, any research underpinning this design standard is not stated. The results presented in this study are more in line with the Austrian and German pavement design standards than they are with the current UK standards in that they suggest a continuous relationship between lane width and deterioration. However, the results presented here do not include extremely narrow lane sections, and also the inclusion of road width, which is not present in either the Austrian of the German design standards.

The UK design guidance considers the channelisation factor of ‘2’ (or 100% difference) based on a theoretical distribution of vehicle positions, going from a notional normal distribution with a particular standard deviation to very channelised traffic with very small standard deviation. These two conditions are considered here to be purely theoretical and it is entirely plausible that they would never occur in reality as perfectly channelised or unchannelised. It seems that these situations have never been tested to check whether or not the distribution of vehicles would ever exist. However, as the spacing between tyres on a vehicle differs, this alone means that a road with different vehicle types and models using the road, there cannot be completely perfect channelisation of both wheel paths. For example; the space between the two front tyres on a HGV is wider than a passenger car. Unless the traffic includes exactly the same vehicles travelling along the length of the road and those vehicles follow each other absolutely perfectly, the distribution of tyre loading would ever be perfectly channelised. This is an impossible scenario that the current UK design guidance considers. Even if the applied channelisation factor of ‘2’ would have been correct, the scenario when this might occur is not possible to exist in reality. The benefit of using the suggested model and channelisation factor found in this research would be to design pavement thicknesses more economically in terms of savings from the materials that would be used.

In addition, it was found that the road camber, every 1 % greater the cross-fall, the nearside wheel path rutting was 0.396 mm greater. The standard deviation in road camber observed resulted in 0.198 mm difference in rut depths. Using the same logic, a 1% increase in the camber relates to 29% increase in design traffic which seems very high. However, the correlation test results (in section 5.3.2) showed that effect is unlikely to be due to the camber alone. It suggests that the camber seems to be combination of camber, curvature and longitudinal gradient (as these variables were correlated with each other in the dataset). From the data set used in this research, where there was a big camber, there was also a sharp curve.

It was still important to keep in the model to correct for its effect. This was not the main point to investigate for this research, however, this is an interesting finding that could form the basis of further work to explore the effect of camber alone on the deterioration of pavements.

The findings presented here could subsequently have an impact on pavement performance. Furthermore, local highway authorities can include the potential impacts on the lifespan of pavements when considering changes to lane widths resulting from the introduction of any road features or other changes to existing highways. For example, local highway authorities considering to remove or introduce on street parking or a cycle lane could include the likely cost implications of increased or reduced maintenance of the pavements that might result due to the changes in the degree of channelisation and the impact of this on the deterioration of the pavement.

In UK pavement management systems, the efficiency, accuracy and quality of information and records maintained by authorities are crucial both to the effective management of the service and to the defence of claims against the authority for alleged failure to maintain (Roads Liaison Group, 2005). Modelling and forecasting of pavement performance requires important factors to be considered, mainly age (years since original construction or last overlay), annual traffic, type and quality of construction and degree and type of damage and degradation in the current state (K. George, Rajagopal, & Lim, 1989; Walsh et al., 2011b).

Recent work has addressed some issues around the deterioration models that underpin pavement management systems. These are related to the performance models for pavement behaviours that need to be developed in order to determine the deterioration mechanisms and to incorporate related maintenance and rehabilitation actions into the model. Specifically, it is suggested to integrate deterioration models that consider uncertainty, such as future cost of maintenance, traffic volumes, and available sources, while incorporating the sources of economic and environmental parameters that explain the heterogeneous nature of pavements (Swei et al., 2015). The use of traffic loading information is incorporated in PMSs to assist in the identification and prioritisation of required maintenance and rehabilitation measures, and pavement prediction models and related optimisation procedures (Van Wijk & Sadzik, 1998).

Further to the benefits in designing a pavement, an application of the representative degree of channelisation patterns can be developed in PMS for modelling the deterioration to indicate the actual damaging effects of laterally distributed traffic loads. Appropriate recognition and implementation of the degree of channelisation in PMS procedures thorough design of pavements can have a significant economic impact on both pavement design and maintenance management plans. This can be achieved by developing detailed deterioration models to better estimate the rates of rutting progression under different degrees of channelisation. In this way, the rates of actual deterioration can be more accurately predicted, triggering rehabilitation interventions when required. This could lead to more efficient use of highway agencies limited resources on maintaining the highway asset. Although, in practice, there are periodic maintenance works including resealing, resurfacing or major patching to delay the need for major rehabilitation, it would be useful for these to be scheduled based on a projected pavement condition including the effects of channelisation.

6.3. Contribution to knowledge

After undertaking the literature review, it was discovered that there is little guidance that explains how to categorise the lateral distribution of traffic flow as either channelised or not channelised which is required in UK pavement design guidance. Firstly, in this research, the measured variation (standard deviation) of lateral vehicle position was considered as the degree of channelisation. This study adds to knowledge regarding channelisation and indicates that it depends on both lane and road width rather than being a binary measure of either channelised or unchannelised as is current used in UK pavement design guidance based on limited research conducted by Kent County Council in 1983 (Walsh et al., 2011a).

The second main contribution to knowledge is how levels of channelisation observed in the real world, affects the deterioration of asphalt pavements. Previous studies have focussed on simulations, or laboratory tests of perfectly channelised or perfectly distributed wheel positions to account for rut levels. However, in the real world these simulation or laboratory conditions do not exist. The tyres of vehicles would never follow each other perfectly in reality. Both extreme conditions are completely theoretical. Therefore, the results presented here represent more realistic results of rutting performance under different degrees of channelisation.

These two contributions to knowledge when brought together enable new guidance to be given to pavement engineers when designing new pavements.

Finally, there was a novel method adopted in this study to measure the vehicle position which is the first known time that this photogrammetric method has been used to account for the perspective caused by the camera being set at an oblique angle to the traffic flow. Despite the level of precision of each position of the vehicle (nearest 50 mm), any error associated with this level of precision is systematic (i.e. it is not expected to relate to any observed or unobserved factors). Therefore, the method was believed to be robust.

6.4. Limitations

While the present investigation produced useful and novel findings, it is necessary to acknowledge the limitations of the study. It is important to note that the results relate to the pavement material considered. Although it may be considered logical that similar differences in rut depths would be found in other asphalt pavement types, in order to demonstrate this, further work would be required. In addition, the minimal rutting meant that the feedback loops between rutting and channelisation could not be explored, which may mean that the effects presented here are an underestimate of the potential magnitude of the association between vehicle wander and rutting for pavements experiencing more severe ruts. That is, as the pavement ages and ruts deepen, the effects of channelisation may accelerate. However, when rutting becomes severe enough for it to affect driving behaviours, it is likely that the pavement has reached a point where it requires maintenance, hence the results presented here ought to be valid for pavement engineers wishing to predict how long it would take a pavement to reach this failure point. How pavements continue to degrade beyond this failure point is perhaps of less interest to pavement engineers.

The variable of speed (not included in the final models as it was not statistically significant) was also maximum of 30 mph in the case study location. There was little variation in the speeds observed in this study. As such, the longitudinal and horizontal forces such associated with different speeds of vehicles on the pavement could not be investigated as part of this study.

Data was only available for 2014, 2017 and 2018. Although the data was provided for 2015 and 2016 years, these appeared to have some anomalies such as pavement conditions appeared to have improved in some locations despite there being no maintenance. There those years of data was excluded from the whole analyses. However, this did not limit this research.

Although the unique geological and climactic conditions found in Portsmouth were constant across the data collection points, the variation in channelisation between the 100 observation points was not expected to be influenced by these conditions.

6.5. Recommendations for further research

Further work could investigate whether the findings from this study apply to extremely narrow road and lane sections, or at other road features such as bus stops, toll gates etc.

Also, the impact of channelisation of traffic could be analysed in different types of pavement in terms of detecting differences in rut depths. The study can easily be repeated for other types of asphalt pavements although on rigid or composite pavement types, rutting is less common.

Further work could gather more detailed rut data for exact locations on the highway, rather than averaging it over 10 m length as was the case in the dataset supplied for this study. Although the actual rut depth data obtained from SCANNER survey (provided by COLAS Ltd.) was believed to be accurate, the precision of the location of the rut depth measurements was the main concern in this second part of the research. The data collected for lateral wander represented an exact location along the case study road whereas rut depth data was averaged over 10 m length. When the rut depth data was superimposed onto the lateral wander data, they were not at the exact same locations. This could have resulted in under representing the true effect of geometry on rutting. For example, the lateral wander data observed for one location where there was also parked cars, but within 10 metres of that location there could be no parked cars. However, the road sections investigated in this research did not have such instantaneous changes in road geometry within 10m of the location of the data collection. The changes in the width of the road and lane were more gradual along the length of pavement sections. Therefore, the fact that the rut data were averaged over 10 metres is not believed to have influenced the results of this study to any substantial degree.

In addition, rutting is only one deterioration mode when the overall pavement performance is considered. It may be the case that there is a different or no relationship between vehicle wander and other deterioration modes, which could be explored in any further work.

Further work could repeat the investigation on sections of road with greater variations in vehicle speeds, curvatures, super elevations etc. in order to determine if these have a significant impact on deterioration, not captured in this study. Particularly, in order to find the effect of camber, curvature and longitudinal gradient on rutting performance, the samples are suggested to include sections with tight curves, or small cambers and all different combinations.

The direction of lane is found in this study to relate to unobserved characteristics that could affect the deterioration of the pavement such as, location of drainage runs, surface temperature, differing compaction levels during construction etc.

In addition, there has been little research on lateral wander performance of Autonomous Vehicle (AV) technology. It is understood that the reduced lateral wander associated with autonomous vehicles could bring high levels of channelisation. As a result of the introduction of more AVs that follow the paths of other vehicles almost perfectly, increased rutting damage would be inevitable, therefore, the design of pavements in the future should consider the potential of high levels of channelisation on all pavement sections. In future, if such a scenario of large number of autonomous vehicles with little lateral wander were to materialise, then the first equation linking the degree of channelisation to the rut depth could be used by pavement engineers to account for the damage that this would otherwise cause to pavements.

6.6. Chapter Summary

This final chapter was to present research findings and conclusions of the study. The contribution of this project to fill knowledge gaps was illustrated. Limitations and recommendation for further research were also outlined.

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Appendices

Appendix A: Research Ethic Form

UNIVERSITY OF PORTSMOUTH

Certificate of Ethics Review

Project Title:	The role of channelisation on the future performance of highway pavements
User ID:	848686
Name:	Renan Sinanmis
Application Date:	10/01/2018 16:57:40

You must download your certificate, print a copy and keep it as a record of this review.

It is your responsibility to adhere to the University Ethics Policy and any Department/School or professional guidelines in the conduct of your study including relevant guidelines regarding health and safety of researchers and University Health and Safety Policy.

It is also your responsibility to follow University guidance on Data Protection Policy:

- General guidance for all data protection issues
- University Data Protection Policy

You are reminded that as a University of Portsmouth Researcher you are bound by the UKRIO Code of Practice for Research; any breach of this code could lead to action being taken following the University's Procedure for the Investigation of Allegations of Misconduct in Research.

Any changes in the answers to the questions reflecting the design, management or conduct of the research over the course of the project must be notified to the Faculty Ethics Committee. **Any changes that affect the answers given in the questionnaire, not reported to the Faculty Ethics Committee, will invalidate this certificate.**

This ethical review should not be used to infer any comment on the academic merits or methodology of the project. If you have not already done so, you are advised to develop a clear protocol/proposal and ensure that it is independently reviewed by peers or others of appropriate standing. A favourable ethical opinion should not be perceived as permission to proceed with the research; there might be other matters of governance which require further consideration including the agreement of any organisation hosting the research.

Governance Checklist

A1-Brief Description Of Project: I am working on modelling and forecasting highway pavement condition. One of the method aims to compare the deterioration of Portsmouth's pavement over time, compared to how they would be expected to have deteriorated if current models were entirely accurate. Particularly, channelisation of traffic and the impact of rutting on pavement deterioration will be examined. The data I would need to use is core sample data, pavement condition survey data and details of pavement maintenance of selected pavement sections. The data will be taken from Portsmouth City Council and Colas.

Certificate Code: 92C7-A6A7-A733-1372-1042-B2B4-0EE2-0724

A2-Faculty: Technology

A3-VoluntarilyReferToFEC: No
A5-AlreadyExternallyReviewed: No
B1-HumanParticipants: No
Human Participants Definition
B2-HumanParticipantsConfirmation: Yes
C6-SafetyRisksBeyondAssessment: No
D2-PhysicalEcologicalDamage: No
D4-HistoricalOrCulturalDamage: No
E1-ContentiousOrIllegal: No
E2-SociallySensitiveIssues: No
F1-InvolvesAnimals: No
F2-HarmfulToThirdParties: No
G1-ConfirmReadEthicsPolicy: Confirmed
G2-ConfirmReadUKRIOCodeOfPractice: Confirmed
G3-ConfirmReadConcordatToSupportResearchIntegrity: Confirmed
G4-ConfirmedCorrectInformation: Confirmed.

Appendix B: General Risk Assessment Form

<table>
<tr><td colspan="2">UNIVERSITY OF PORTSMOUTH
ASSESSING OUR RISKS –
GENERAL RISK ASSESSMENT FORM</td><td colspan="5">Calculate: **Probability** multiplied by **severity** for No/Post control scores.
NB: For scores of 10 (High), or more contact the health & safety department for further advice.</td></tr>
<tr><td>Site/Department: SCES, Survey of traffic in Portsmouth</td><td>Severity
Probability</td><td>Minor injury
1</td><td>Lost time/ Ill Health
2</td><td>Major / >3 days
3</td><td>Perm. Disability
4</td><td>Fatal
5</td></tr>
<tr><td rowspan="2">Task/Activity/Area:
Video surveillance of roads in and around Portsmouth using a mobile phone to collect the data.</td><td>Highly Unlikely 1</td><td>**1**</td><td>**2**</td><td>**3**</td><td>**4**</td><td>**5**</td></tr>
<tr><td>Unlikely 2</td><td>**2**</td><td>**4**</td><td>**6**</td><td>**8**</td><td>**10**</td></tr>
</table>

<table>
<tr><td colspan="2">Notes:
(Including details of previous accidents/incidents)

Hand held in first instance. This will form the first pilot of the data collection. Typically short periods of time (5 to 10 minutes). Roads will be selected that have relatively slow speeds and where the surveillance can be collected safely.</td><td>Possible

3</td><td>3</td><td>6</td><td>9</td><td>12</td><td>15</td></tr>
<tr><td colspan="2"></td><td>Probable

4</td><td>4</td><td>8</td><td>12</td><td>16</td><td>20</td></tr>
<tr><td>RA Team:
(Mgr, Supervisor, EHS Adviser, Safety Rep, Employee, minimum is 2 people)

Lee Woods and Renan Sinanmis</td><td>Date of RA:

23rd October 2017.</td><td>Certain

5</td><td>5</td><td>10</td><td>15</td><td>20</td><td>25</td></tr>
<tr><td colspan="8">People at risk: Employees and Visitors
(e.g., visitors, contractors, hauliers, members of the public, operators, engineers, other employees etc)

Lee Woods and Renan Sinanmis. Drivers and other road users.</td></tr>
</table>

Dept Manager (Print Name):	Lee Woods	Signature:	
Review Date	Prior to next phase of pilot	Review Date	

Identified hazards or Injury causes, highlighting risks (Injury focused - see checklist)	Score -No controls (Probability x Severity = calculation)	**Controls/Procedures/Key Behaviours** **(existing controls, information, training etc)**	Score - Post Controls (Calculation)	**Further action required**	**Action Priority (H/M/L)**
Risk of being struck by moving vehicle.	2x5=10	Make sure that we are stood in a safe area well away from the traffic. High vis.	1x5=5	None	M

Identified hazards or Injury causes, highlighting risks (Injury focused - see checklist)	Score -No controls (Probability x Severity = calculation)	**Controls/Procedures/Key Behaviours** **(existing controls, information, training etc)**	Score - Post Controls (Calculation)	**Further action required**	**Action Priority (H/M/L)**
Causing a road traffic accident due to drivers being distracted by the survey	2x5=10	Collect the data from an unobtrusive position where drivers are less likely to be distracted. Collect the data in areas where the vehicle speeds are lower. Collect the data where there are fewer vulnerable road users.	1x5=5	None	M
Exposure to cold and wet weather	4x2=8	Wear sensible clothing and limit exposure time to poor weather.	2x2=4	None	L

Identified hazards or Injury causes, highlighting risks (Injury focused - see checklist)	Score -No controls (Probability x Severity = calculation)	**Controls/Procedures/Key Behaviours** **(existing controls, information, training etc)**	Score - Post Controls (Calculation)	**Further action required**	**Action Priority (H/M/L)**
Risk of assault from driver/member of the public	2x3=6	Carryout data collection in an area where others are present. Carry out data collection as a pair. Keep mobile phones to hand should they be required.	1x3=3	None	L

Appendix C: Data Analysed in this research

Section	Width lane [m]	Width road [m]	Rut Year	Standard Deviation [m]
ClearenceParade_1	7.6910	15.382	2018	0.4304277400
ClearenceParade_2	6.1662	16.700	2018	0.4519543940
ClearenceParade_3	6.1101	11.850	2018	0.3550896090
ClearenceParade_4	6.3144	13.250	2018	0.3023453100
ClearenceParade_5	6.1681	13.050	2014	0.3153045500
ClearenceParade_6	5.4604	14.120	2018	0.4450055260
ClearenceParade_7	3.8750	6.200	2018	0.1623216680
ClearenceParade_8	4.9570	9.000	2017	0.1978112320
ClearenceParade_9	4.6406	5.500	2017	0.1296298160
ClearenceParade_10	4.4726	11.450	2014	0.4989965020
ClearenceParade_11	5.2464	11.100	2017	0.4140275720
ClearenceParade_12	7.5406	12.700	2018	0.5478643150
ClearenceParade_13	13.8328	22.700	2018	0.7795590920
ClearenceParade_14	9.4878	22.700	2017	0.8577157490
ClearenceParade_15	8.4238	22.700	2017	0.5246591430
ClearenceParade_16	14.1875	22.700	2018	0.7805951320
ClearenceParade_17	7.1112	15.300	2018	0.5790789220
ClearenceParade_18	6.2800	15.300	2014	0.4705081470
ClearenceParade_19	5.6777	15.300	2014	0.5032525750
ClearenceParade_20	6.7535	15.300	2018	0.3869323610
ClearenceParade_21	6.6159	15.122	2018	0.3827342310
ClearenceParade_22	5.6179	15.300	2014	0.3627860860
ClearenceParade_23	6.9328	15.300	2018	0.5078952770
ClearenceParade_24	5.7972	15.300	2014	0.3259936090
ClearenceParade_25	7.6500	15.300	2018	0.6092922980
ClearenceParade_26	6.5250	13.050	2018	0.2958057110
ClearenceParade_27	7.9013	13.050	2014	0.2567114110
ClearenceParade_28	6.7289	13.050	2017	0.5435655310
ClearenceParade_29	5.9093	12.200	2017	0.2950321370
ClearenceParade_30	7.5142	16.874	2018	0.3218522890
ClearenceParade_31	10.2167	16.874	2017	0.5889854420
ClearenceParade_32	5.8469	16.818	2018	0.6943242050
ClearenceParade_33	7.6864	16.818	2014	0.4173267280
ClearenceParade_34	7.8244	16.554	2018	0.6183405970
ClearenceParade_35	6.5311	16.554	2017	0.6151109850
ClearenceParade_36	8.2868	16.704	2018	0.7003610670
ClearenceParade_37	8.4767	16.822	2017	0.5913161930
ClearenceParade_38	8.8710	16.822	2018	0.7104174450
ClearenceParade_39	8.5150	16.768	2018	0.5483971670

ClearenceParade_40	7.8600	16.768	2017	0.6339575170
ClearenceParade_41	5.8127	13.053	2014	0.5243838330
ClearenceParade_42	4.1993	13.110	2018	0.3186325460
ClearenceParade_43	10.6419	14.234	2014	0.6444434490
ClearenceParade_44	5.3378	14.234	2018	0.3057789680
ClearenceParade_45	7.0649	16.442	2014	0.4331516240
ClearenceParade_46	7.1723	15.050	2018	0.4682940240
ClearenceParade_47	6.2138	14.203	2014	0.4136767050
ClearenceParade_48	3.8869	14.215	2017	0.4207832460
ClearenceParade_49	5.1362	14.292	2014	0.3154435190
ClearenceParade_50	7.7800	15.560	2014	0.6331727970
ClearenceParade_51	4.4133	13.450	2014	0.4060038000
ClearenceParade_52	4.3666	14.150	2017	0.3629365960
SouthParade_53	7.2600	7.617	2014	0.4061719890
SouthParade_54	6.5307	14.538	2014	0.4692157090
SouthParade_56	4.5190	14.461	2014	0.4169356450
SouthParade_57	7.1995	14.399	2018	0.4583077900
SouthParade_58	5.7531	14.299	2017	0.4180783690
SouthParade_59	5.2504	14.299	2018	0.4201302550
SouthParade_60	5.3816	14.351	2017	0.4675172380
SouthParade_61	5.3200	14.351	2018	0.4249004740
SouthParade_62	5.5738	14.269	2017	0.3433063990
SouthParade_63	5.1837	14.269	2018	0.3288864830
SouthParade_64	7.5278	14.170	2017	0.3661146400
SouthParade_65	5.3138	14.170	2018	0.3606598300
SouthParade_66	5.3546	14.279	2014	0.3724012140
SouthParade_67	5.7862	14.243	2018	0.4230122550
SouthParade_68	5.4480	14.528	2018	0.3951000960
SouthParade_69	5.4735	14.596	2014	0.3712813030
SouthParade_70	5.4735	14.596	2018	0.4972812240
SouthParade_71	5.5140	14.704	2014	0.3269575380
SouthParade_72	4.5950	14.704	2018	0.3911945510
SouthParade_73	3.8465	8.792	2018	0.2943563390
SouthParade_74	4.6708	8.792	2017	0.3060250400
SouthParade_76	6.7467	14.393	2017	0.5706042370
SouthParade_77	4.4978	14.393	2018	0.3689199080
SouthParade_78	5.0893	16.286	2018	0.3380455810
SouthParade_79	6.2968	15.500	2018	0.6599000970
SouthParade_80	6.7812	15.500	2014	0.4749037350
SouthParade_81	7.2365	17.813	2014	0.4446827590
SouthParade_82	7.0973	17.813	2018	0.5289009020
SouthParade_83	5.8781	15.675	2017	0.4165045410
SouthParade_84	6.8236	15.597	2018	0.3947563680
SouthParade_85	7.7660	15.532	2014	0.4397528680
SouthParade_86	7.7465	15.493	2014	0.6972947820

SouthParade_87	6.3098	15.532	2018	0.4663165900
SouthParade_88	8.3100	16.620	2018	0.4817003260
SouthParade_89	8.8235	17.647	2014	0.6263046050
SouthParade_90	6.3890	16.356	2017	0.6442566280
SouthParade_91	6.1335	16.356	2018	0.3143122110
SouthParade_92	4.9375	17.154	2018	0.3195758960
SouthParade_93	7.6344	17.450	2018	0.4036257730
SouthParade_94	7.0018	16.004	2018	0.4695971130
SouthParade_95	5.9389	16.004	2017	0.4808470570
SouthParade_96	5.2014	11.889	2017	0.5211413080
SouthParade_97	4.4583	11.889	2018	0.4035548220
SouthParade_98	4.2933	11.449	2018	0.4607859240
SouthParade_99	3.3989	11.449	2017	0.3226699980
SouthParade_100	3.6876	8.429	2017	0.2682989240

Nearside Rut Depth [mm]	AADT	Cars Morning Peak	LGVs Morning Peak	HGVs Morning Peak
2.10	4602.00	263.00	10.00	1.00
3.60	4602.00	266.00	24.00	1.00
0.90	4602.00	266.00	24.00	1.00
1.30	4602.00	263.00	10.00	1.00
2.60	4603.00	113.00	11.00	0.00
1.30	4602.00	241.00	25.00	5.00
4.10	4602.00	336.00	26.00	4.00
2.60	4602.00	263.00	10.00	1.00
0.60	4603.00	113.00	11.00	0.00
0.80	4603.00	113.00	11.00	0.00
2.50	4602.00	263.00	10.00	1.00
1.40	4602.00	263.00	10.00	1.00
1.20	4602.00	263.00	10.00	1.00
0.30	4603.00	113.00	11.00	0.00
0.00	4603.00	113.00	11.00	0.00
0.80	4602.00	263.00	10.00	1.00
0.30	4602.00	263.00	10.00	1.00
0.20	4603.00	113.00	11.00	0.00
2.10	4603.00	113.00	11.00	0.00
1.80	4602.00	263.00	10.00	1.00
1.00	4602.00	263.00	10.00	1.00
0.10	4603.00	113.00	11.00	0.00
2.30	4602.00	263.00	10.00	1.00

0.60	4603.00	113.00	11.00	0.00
1.40	4602.00	263.00	10.00	1.00
2.30	4602.00	263.00	10.00	1.00
2.20	4603.00	113.00	11.00	0.00
2.90	4603.00	105.00	7.00	1.00
5.40	4603.00	105.00	7.00	1.00
2.60	4602.00	266.00	24.00	1.00
3.30	4603.00	105.00	7.00	1.00
0.40	4602.00	266.00	24.00	1.00
2.30	4603.00	105.00	7.00	1.00
1.60	4602.00	266.00	24.00	1.00
3.60	4603.00	105.00	7.00	1.00
1.40	4602.00	266.00	24.00	1.00
2.60	4603.00	105.00	7.00	1.00
0.20	4602.00	266.00	24.00	1.00
0.10	4602.00	266.00	24.00	1.00
1.20	4603.00	105.00	7.00	1.00
2.00	4603.00	105.00	7.00	1.00
1.90	4602.00	266.00	24.00	1.00
1.90	4603.00	105.00	7.00	1.00
2.40	4602.00	266.00	24.00	1.00
1.20	4603.00	133.00	12.00	2.00
3.30	4602.00	241.00	25.00	5.00
1.10	4603.00	133.00	12.00	2.00
1.70	4603.00	133.00	12.00	2.00
0.90	4603.00	133.00	12.00	2.00
2.10	4603.00	133.00	12.00	2.00
0.20	4603.00	133.00	12.00	2.00
2.60	4603.00	133.00	12.00	2.00
3.90	4732.00	84.00	11.00	4.00
0.30	4732.00	84.00	11.00	4.00
0.00	4732.00	84.00	11.00	4.00
3.00	4732.00	193.00	18.00	2.00
0.60	4732.00	84.00	11.00	4.00
3.50	4732.00	193.00	18.00	2.00
0.10	4732.00	84.00	11.00	4.00
2.70	4732.00	193.00	18.00	2.00
0.10	4732.00	84.00	11.00	4.00
3.20	4732.00	193.00	18.00	2.00
0.20	4732.00	101.00	13.00	1.00
3.50	4732.00	200.00	16.00	3.00
0.70	4732.00	101.00	13.00	1.00
3.80	4732.00	200.00	16.00	3.00
3.40	4732.00	200.00	16.00	3.00
0.00	4732.00	101.00	13.00	1.00

3.50	4732.00	200.00	16.00	3.00
0.00	4732.00	101.00	13.00	1.00
4.20	4732.00	200.00	16.00	3.00
3.60	4732.00	200.00	16.00	3.00
1.90	4732.00	101.00	13.00	1.00
1.10	4732.00	120.00	8.00	2.00
1.80	4732.00	233.00	18.00	1.00
2.50	4732.00	233.00	18.00	1.00
1.20	4732.00	241.00	17.00	0.00
1.80	4732.00	137.00	9.00	0.00
0.60	4732.00	137.00	9.00	0.00
2.20	4732.00	241.00	17.00	0.00
0.80	4732.00	137.00	9.00	0.00
4.10	4732.00	241.00	17.00	0.00
0.10	4732.00	137.00	9.00	0.00
0.40	4732.00	137.00	9.00	0.00
3.80	4732.00	241.00	17.00	0.00
2.30	4732.00	241.00	17.00	0.00
1.70	4732.00	137.00	9.00	0.00
1.00	4732.00	131.00	18.00	0.00
1.20	4732.00	200.00	9.00	0.00
1.20	4732.00	200.00	9.00	0.00
3.80	4732.00	200.00	9.00	0.00
5.10	4732.00	200.00	9.00	0.00
0.30	4732.00	131.00	18.00	0.00
1.90	4732.00	131.00	18.00	0.00
1.90	4732.00	200.00	9.00	0.00
0.60	4732.00	192.00	23.00	0.00
2.40	4732.00	171.00	10.00	0.00
2.10	4732.00	171.00	10.00	0.00

Buses Morning Peak	Cars Evening Peak	LGVs Evening Peak	HGVs Evening Peak	Buses Evening Peak
0.00	105.00	11.00	1.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00
1.00	133.00	9.00	1.00	0.00
4.00	128.00	9.00	1.00	3.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00

0.00	250.00	18.00	3.00	1.00
0.00	105.00	11.00	1.00	0.00
0.00	105.00	11.00	1.00	0.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00
0.00	250.00	18.00	3.00	1.00
0.00	105.00	11.00	1.00	0.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00
0.00	250.00	18.00	3.00	1.00
0.00	105.00	11.00	1.00	0.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00
0.00	105.00	11.00	1.00	0.00
0.00	105.00	11.00	1.00	0.00
0.00	250.00	18.00	3.00	1.00
0.00	232.00	20.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	232.00	20.00	0.00	0.00
0.00	112.00	14.00	0.00	0.00
0.00	274.00	14.00	0.00	1.00
1.00	133.00	9.00	1.00	0.00
0.00	274.00	14.00	0.00	1.00
0.00	274.00	14.00	0.00	1.00
0.00	274.00	14.00	0.00	1.00
0.00	274.00	14.00	0.00	1.00
0.00	274.00	14.00	0.00	1.00
0.00	274.00	14.00	0.00	1.00
0.00	276.00	15.00	1.00	0.00
0.00	276.00	15.00	1.00	0.00

0.00	276.00	15.00	1.00	0.00
0.00	152.00	7.00	0.00	0.00
0.00	276.00	15.00	1.00	0.00
0.00	152.00	7.00	0.00	0.00
0.00	276.00	15.00	1.00	0.00
0.00	152.00	7.00	0.00	0.00
0.00	276.00	15.00	1.00	0.00
0.00	152.00	7.00	0.00	0.00
0.00	219.00	11.00	0.00	0.00
2.00	115.00	5.00	0.00	0.00
0.00	219.00	11.00	0.00	0.00
2.00	115.00	5.00	0.00	0.00
2.00	115.00	5.00	0.00	0.00
0.00	219.00	11.00	0.00	0.00
2.00	115.00	5.00	0.00	0.00
0.00	219.00	11.00	0.00	0.00
2.00	115.00	5.00	0.00	0.00
2.00	115.00	5.00	0.00	0.00
0.00	219.00	11.00	0.00	0.00
0.00	241.00	6.00	0.00	0.00
0.00	132.00	8.00	0.00	0.00
0.00	132.00	8.00	0.00	0.00
0.00	154.00	10.00	0.00	0.00
0.00	220.00	19.00	0.00	0.00
0.00	220.00	19.00	0.00	0.00
0.00	154.00	10.00	0.00	0.00
0.00	220.00	19.00	0.00	0.00
0.00	154.00	10.00	0.00	0.00
0.00	220.00	19.00	0.00	0.00
0.00	220.00	19.00	0.00	0.00
0.00	154.00	10.00	0.00	0.00
0.00	154.00	10.00	0.00	0.00
0.00	220.00	19.00	0.00	0.00
0.00	204.00	21.00	0.00	0.00
0.00	143.00	7.00	0.00	0.00
0.00	143.00	7.00	0.00	0.00
0.00	143.00	7.00	0.00	0.00
0.00	143.00	7.00	0.00	0.00
0.00	204.00	21.00	0.00	0.00
0.00	204.00	21.00	0.00	0.00
0.00	143.00	7.00	0.00	0.00
8.00	175.00	7.00	0.00	8.00
7.00	212.00	19.00	0.00	6.00
7.00	212.00	19.00	0.00	6.00

Parked cars	Central reservation	Nearside Hatching	Zigzag lines	Cycle lane
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	1.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	1.00	2.00	2.00
2.00	1.00	2.00	1.00	1.00
2.00	1.00	2.00	2.00	1.00
2.00	1.00	2.00	2.00	1.00
2.00	1.00	2.00	2.00	1.00
2.00	1.00	2.00	2.00	1.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
2.00	2.00	1.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	1.00	2.00
2.00	2.00	2.00	1.00	2.00
2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
1.00	1.00	2.00	2.00	2.00

2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	1.00	2.00
2.00	1.00	2.00	1.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	2.00	2.00	2.00
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1.00	2.00	2.00	2.00	2.00
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1.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
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2.00	2.00	1.00	1.00	2.00
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2.00	2.00	1.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
1.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00

2.00	2.00	1.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00
2.00	1.00	1.00	2.00	2.00
2.00	1.00	1.00	2.00	1.00
2.00	1.00	2.00	2.00	2.00
2.00	1.00	1.00	2.00	2.00
2.00	1.00	1.00	2.00	2.00
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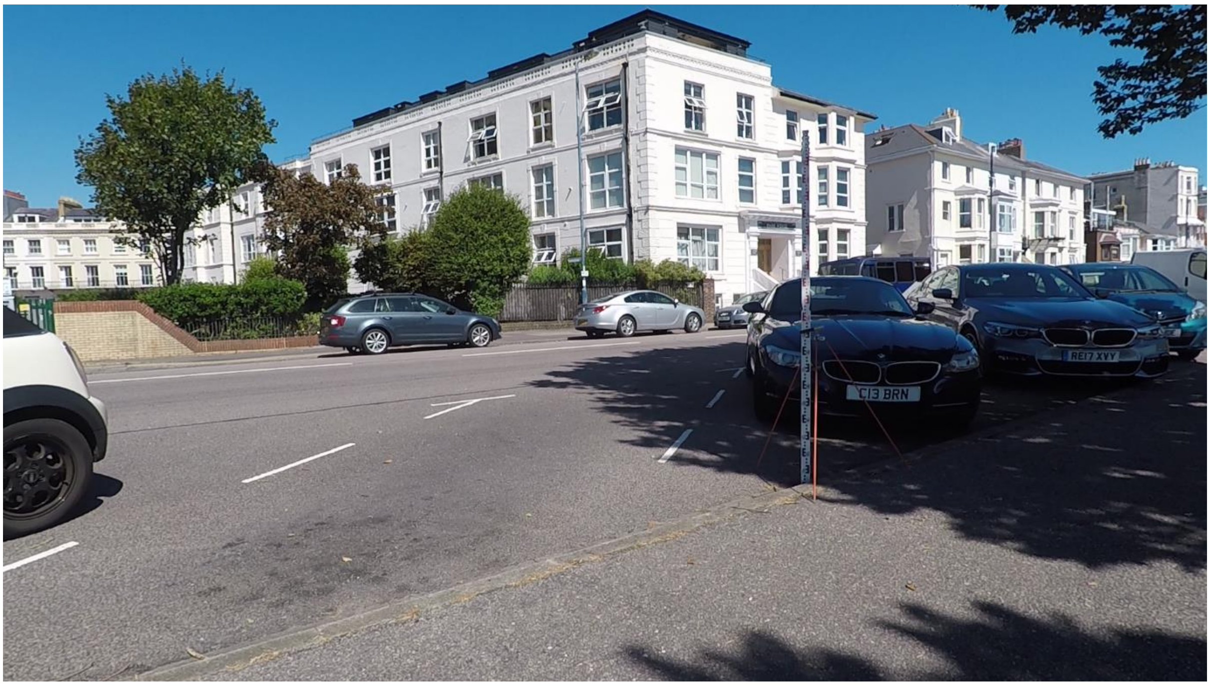
2.00	1.00	2.00	2.00	2.00
2.00	2.00	2.00	1.00	2.00
2.00	2.00	2.00	1.00	1.00
2.00	2.00	1.00	2.00	1.00
2.00	2.00	2.00	2.00	1.00
2.00	2.00	2.00	1.00	1.00

Lane	**Curvature**	**Camber**
2	243.77	2.50
2	488.21	2.00
2	2000.00	2.50
2	-239.16	2.80
1	-373.31	5.80
2	456.98	1.30
2	-277.74	3.50
2	-223.88	2.90
1	0.01	2.90
1	518.55	6.00
2	0.00	3.70
2	127.88	1.90
2	107.69	1.40
1	0.01	3.80
1	0.01	3.80
2	141.69	1.40
2	176.56	2.40
1	145.52	3.30
1	497.20	3.90
2	268.50	2.60
2	2000.00	1.80
1	1881.87	4.90
2	2000.00	1.90
1	2000.00	4.30
2	2000.00	1.60

2	867.43	2.60
1	300.28	3.60
1	0.00	5.60
1	0.00	5.40
2	633.81	2.30
1	0.00	5.20
2	2000.00	1.60
1	0.00	4.30
2	2000.00	1.80
1	0.00	5.30
2	2000.00	3.00
1	0.00	6.00
2	2000.00	2.30
2	455.03	2.00
1	0.00	6.40
1	118.92	6.40
2	268.27	2.40
1	81.17	3.90
2	283.66	2.90
1	60.73	3.30
2	75.09	4.40
1	78.15	2.30
1	0.00	6.10
1	590.49	5.70
1	58.55	4.00
1	510.19	2.30
1	0.00	5.20
1	46.23	6.00
1	539.88	3.80
1	93.91	3.30
2	951.02	2.90
1	0.00	3.70
2	1670.72	3.10
1	0.00	3.00
2	857.95	2.90
1	0.00	2.00
2	1554.47	3.10
1	0.00	2.30
2	2000.00	3.80
1	1813.30	3.50
2	382.38	3.80
2	1982.72	1.10
1	2000.00	2.50
2	135.15	1.40
1	2000.00	2.30

2	2000.00	2.00
2	457.89	2.60
1	0.00	3.40
1	0.00	1.50
2	824.11	2.80
2	1473.93	1.90
2	676.51	1.80
1	505.95	3.50
1	490.68	4.30
2	1275.56	2.20
1	0.00	5.20
2	698.88	1.60
1	476.97	3.90
1	463.29	3.10
2	897.92	3.80
2	641.71	1.40
1	186.12	2.80
1	0.01	3.80
2	67.22	-1.30
2	67.22	-1.30
2	108.97	0.00
2	-288.27	2.00
1	0.00	2.20
1	0.00	1.10
2	438.71	2.50
2	2000.00	-0.30
1	0.00	3.80
1	0.00	6.10

Appendix D: Pictures of road sections



Clarence Parade 1

Clarence Parade 2

Clarence Parade 3

Clarence Parade 4

Clarence Parade 5

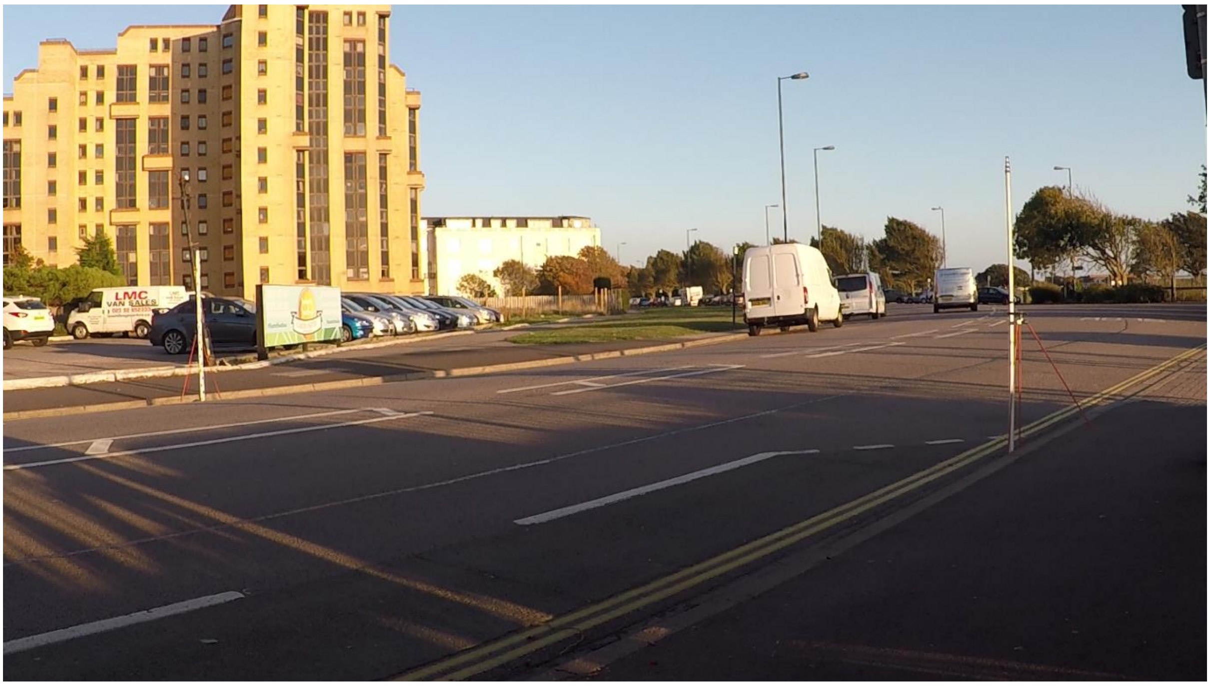
Clarence Parade 6

Clarence Parade 7

Clarence Parade 8

Clarence Parade 9

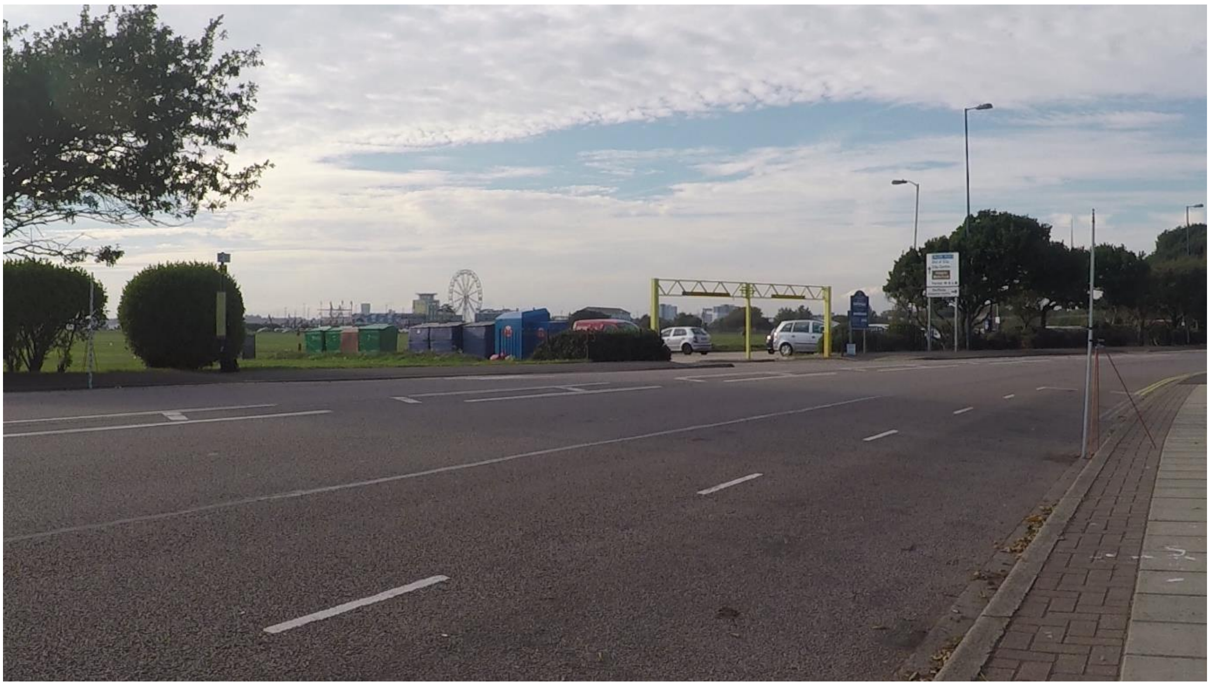
Clarence Parade 10



Clarence Parade 11

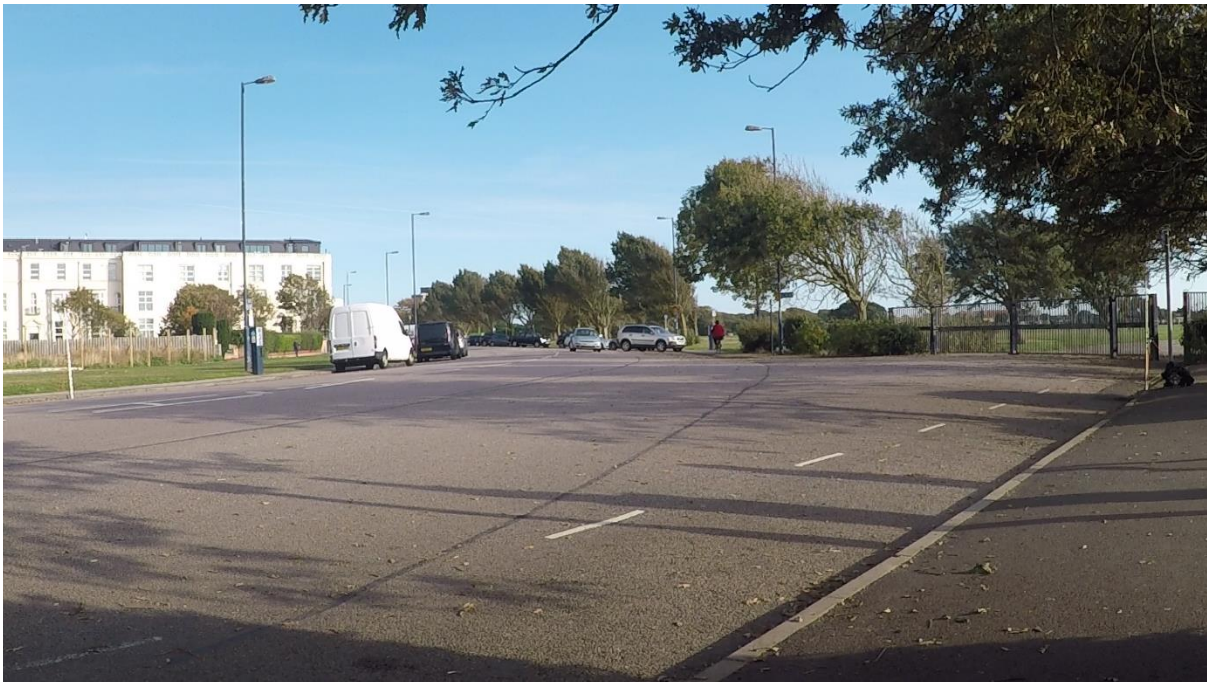
Clarence Parade 12

Clarence Parade 13



Clarence Parade 14

Clarence Parade 15

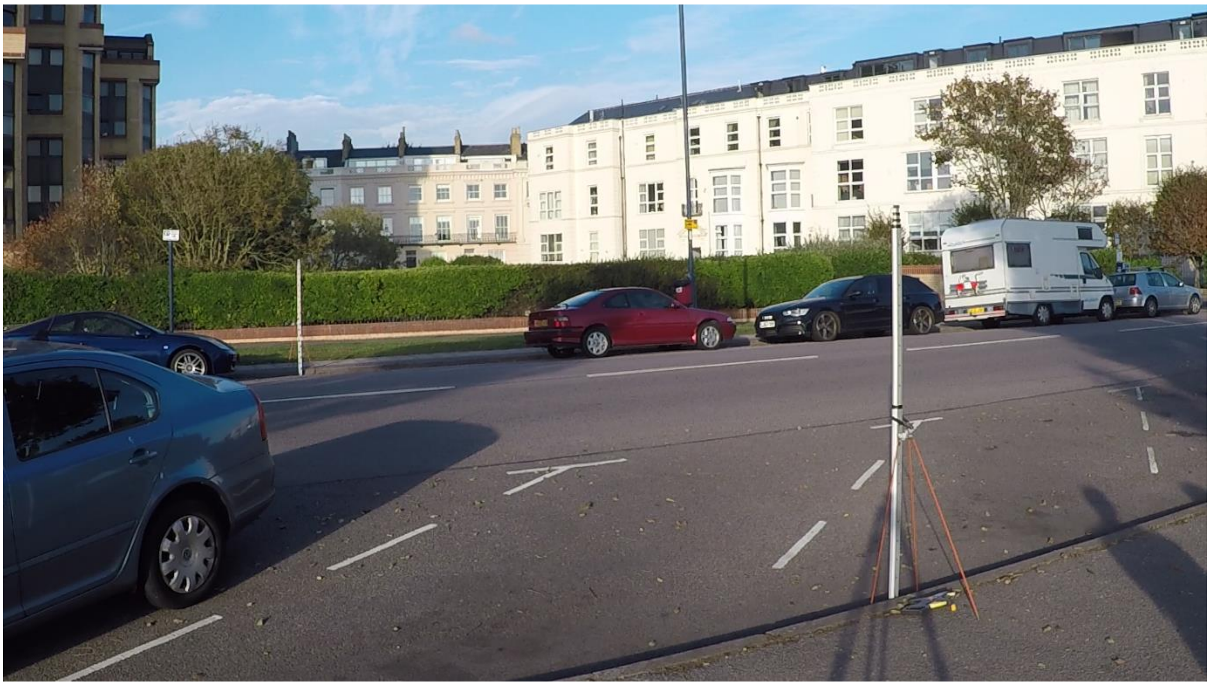


Clarence Parade 16

Clarence Parade 17

Clarence Parade 18

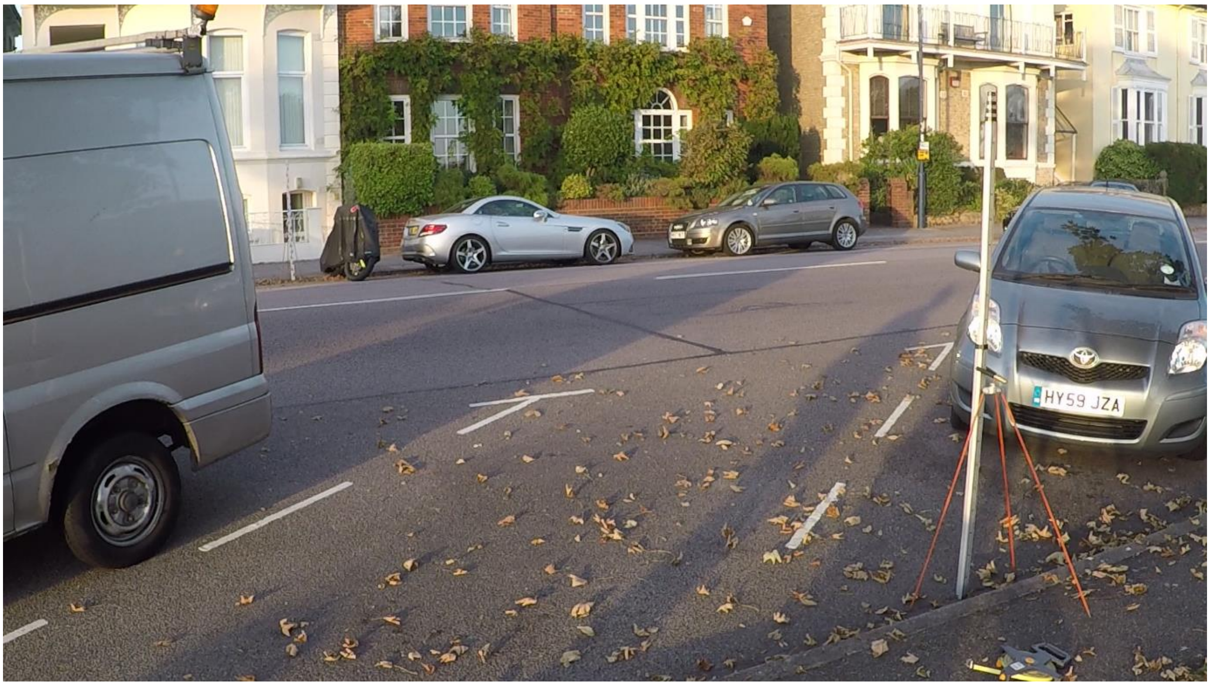
Clarence Parade 19



Clarence Parade 20

Clarence Parade 21

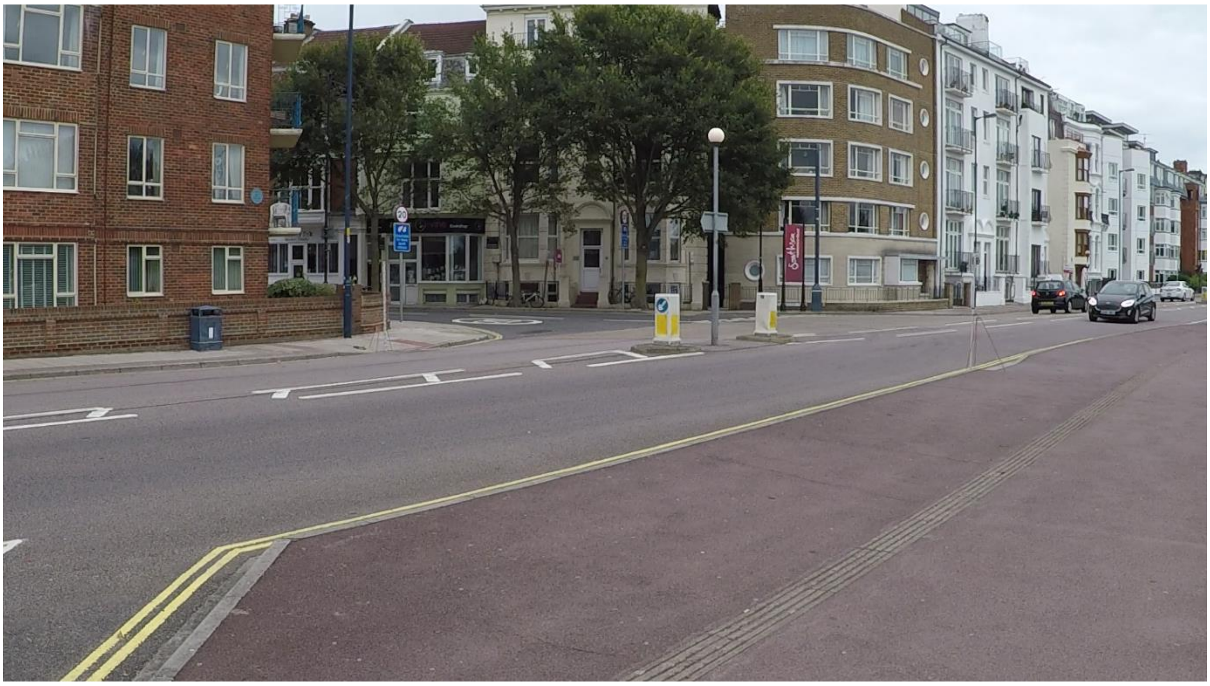
Clarence Parade 22



Clarence Parade 23

Clarence Parade 24

Clarence Parade 25



Clarence Parade 26

Clarence Parade 27

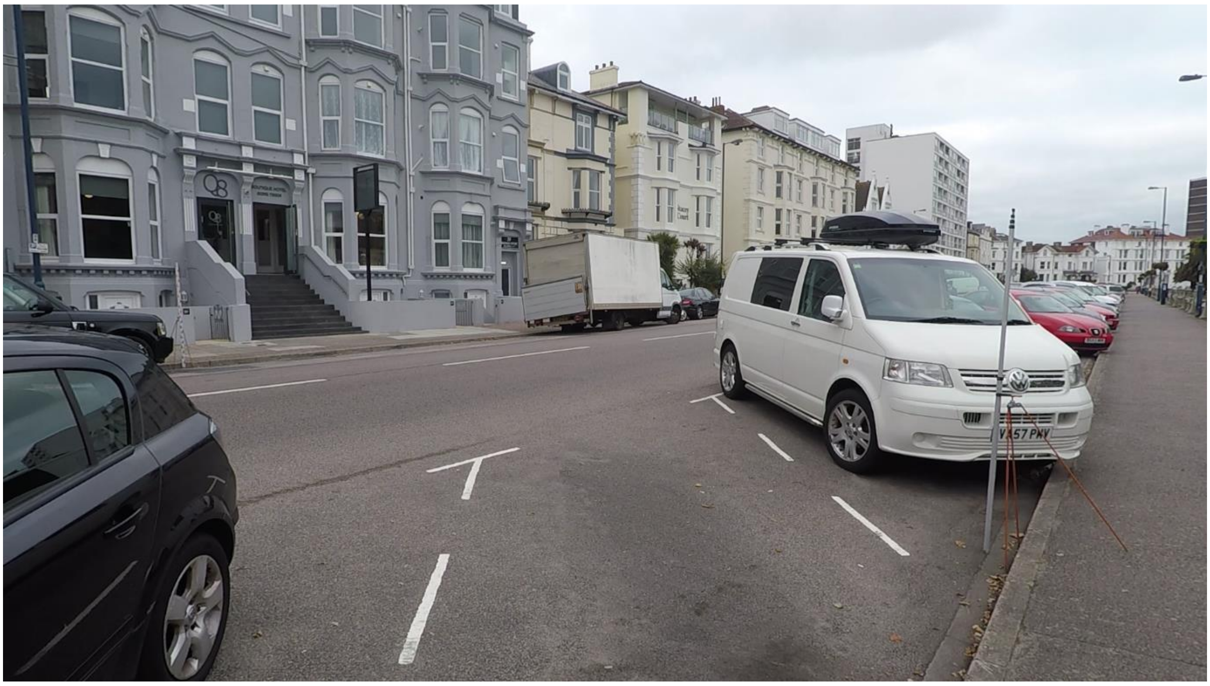
Clarence Parade 28

Clarence Parade 29

Clarence Parade 30

Clarence Parade 31

Clarence Parade 32



Clarence Parade 33

Clarence Parade 34

Clarence Parade 35

Clarence Parade 36

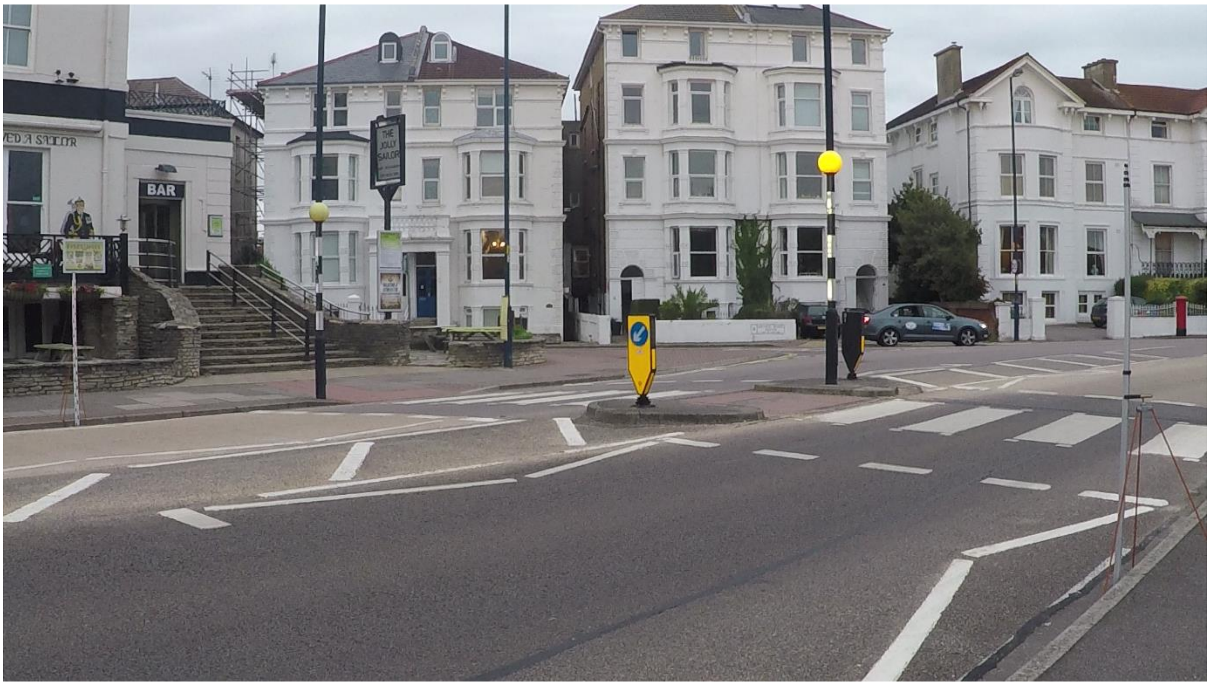
Clarence Parade 37

Clarence Parade 38

Clarence Parade 39

Clarence Parade 40

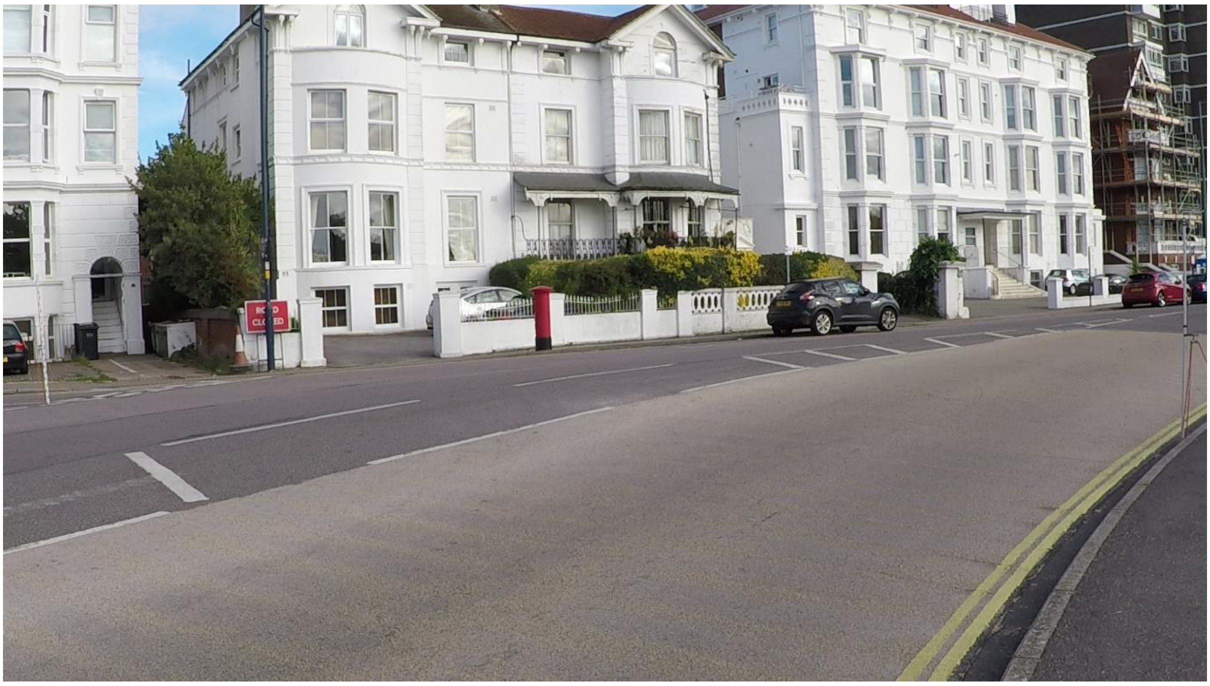
Clarence Parade 41



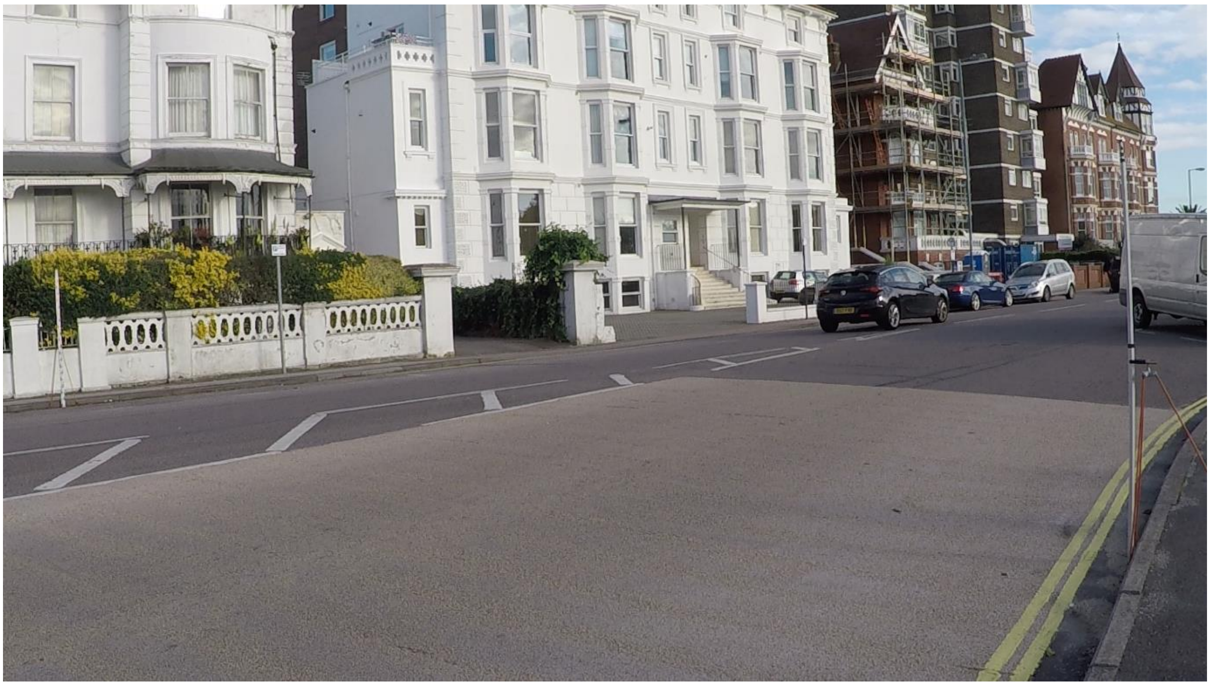
Clarence Parade 42

Clarence Parade 43

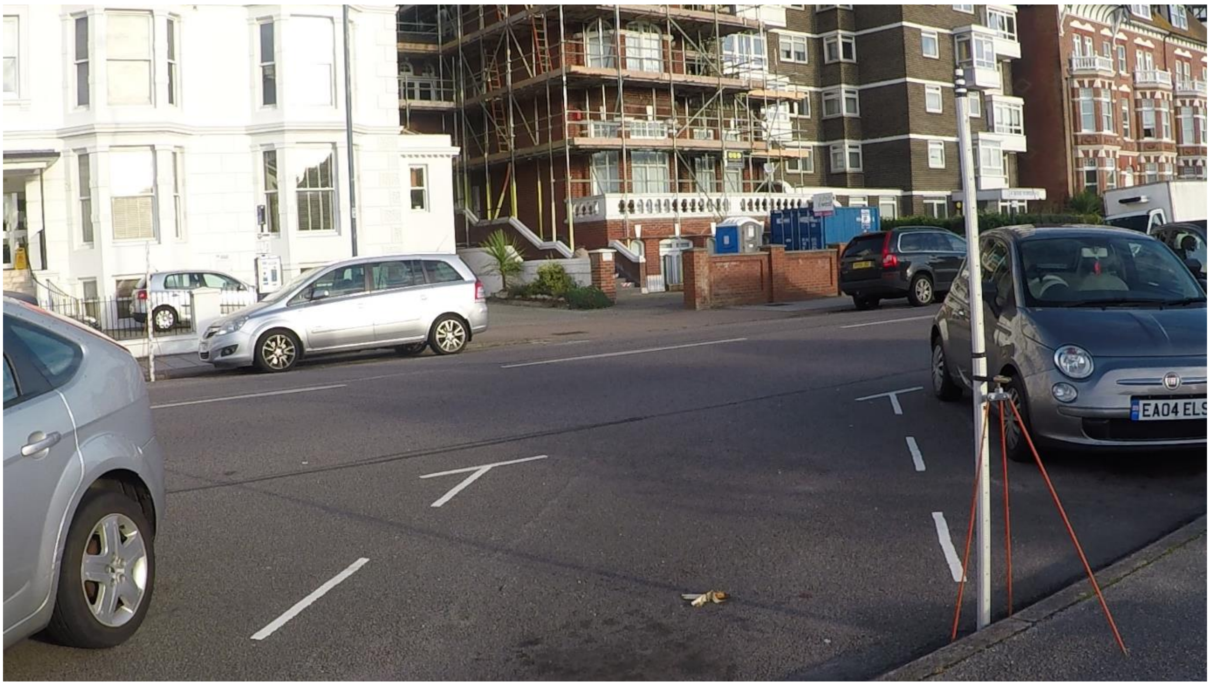
Clarence Parade 44



Clarence Parade 45



Clarence Parade 46



Clarence Parade 47

Clarence Parade 48

Clarence Parade 49

Clarence Parade 50

Clarence Parade 51

Clarence Parade 52

South Parade 53

South Parade 54

South Parade 55

South Parade 56

South Parade 57

South Parade 58

South Parade 59

South Parade 60

South Parade 61

South Parade 62

South Parade 63

South Parade 64

South Parade 65

South Parade 66

South Parade 67

South Parade 68

South Parade 69

South Parade 70

South Parade 71

South Parade 72

South Parade 73

South Parade 74

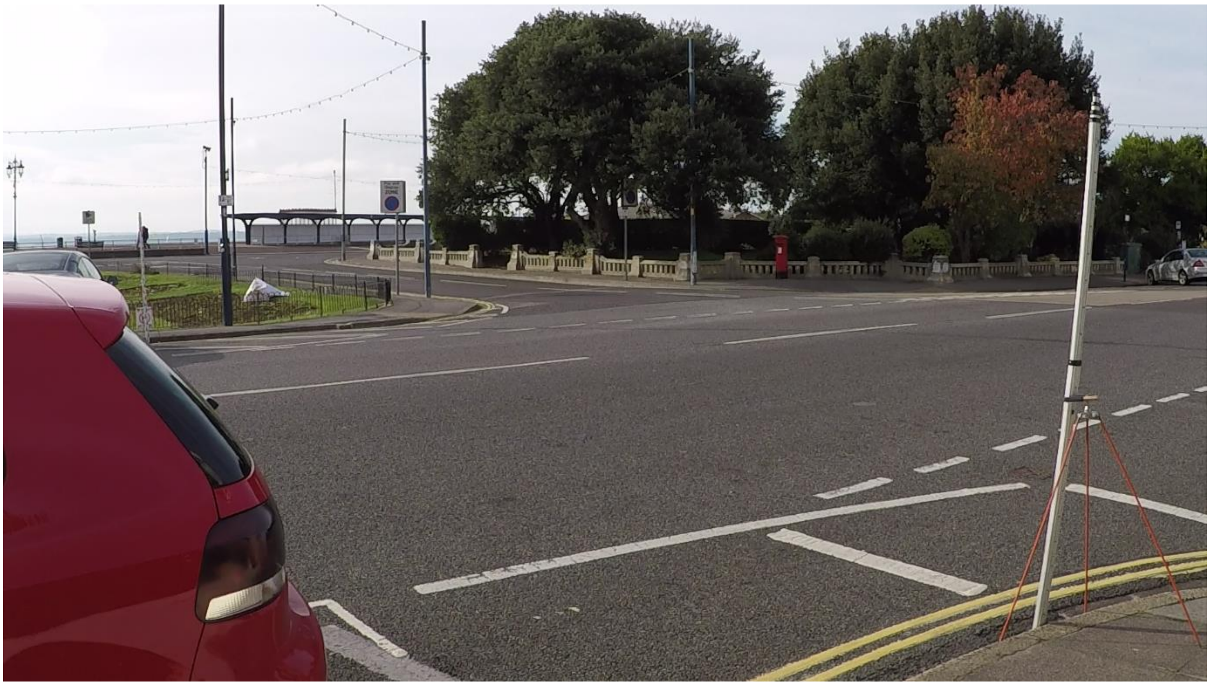
South Parade 75

South Parade 76

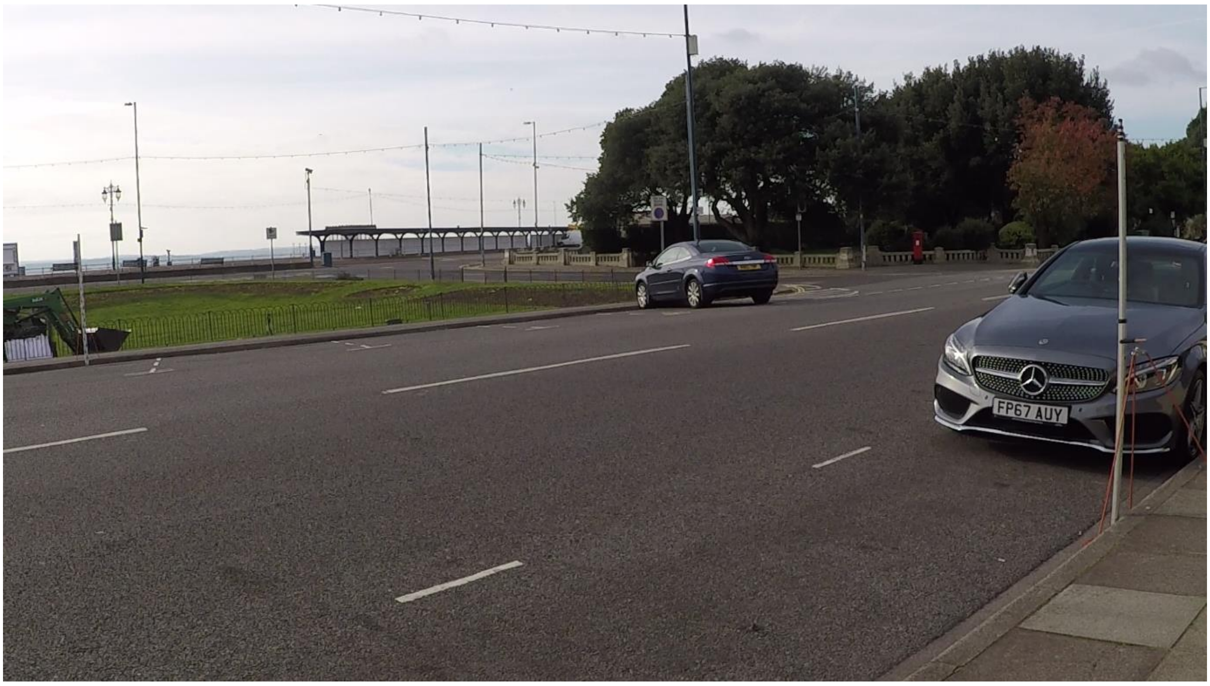
South Parade 77

South Parade 78

South Parade 79



South Parade 80



South Parade 81

South Parade 82

South Parade 83

South Parade 84

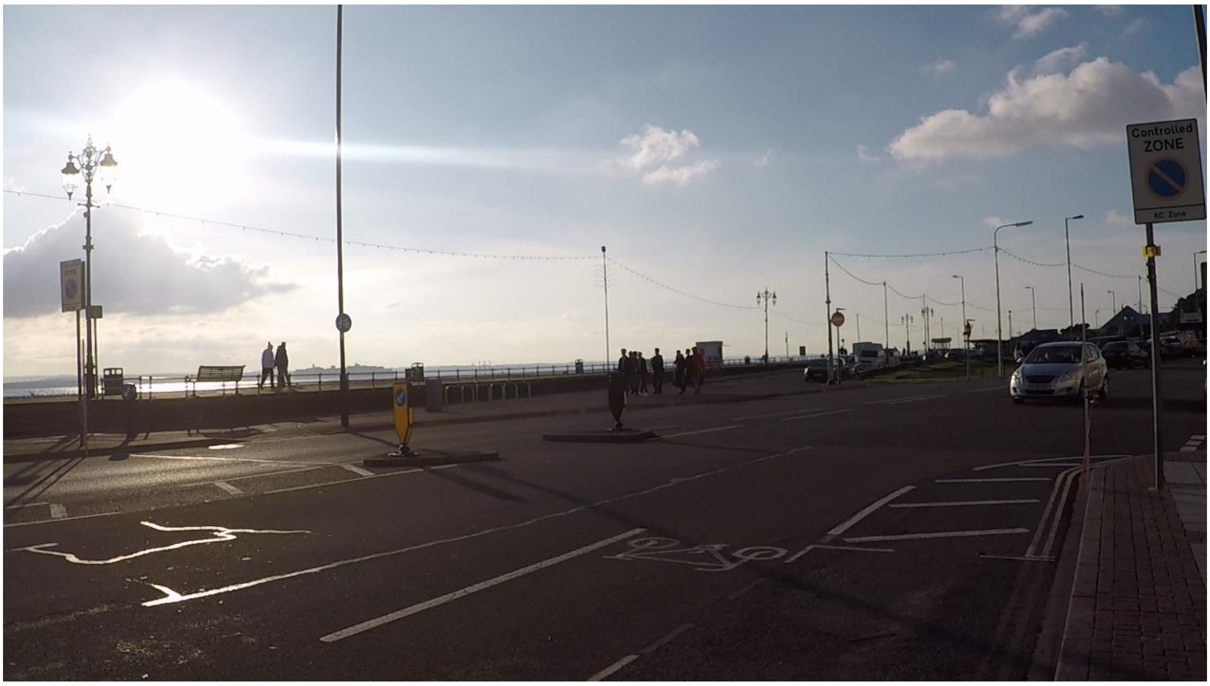
South Parade 85

South Parade 86

South Parade 87

South Parade 88

South Parade 89



South Parade 90

South Parade 91

South Parade 92

South Parade 93

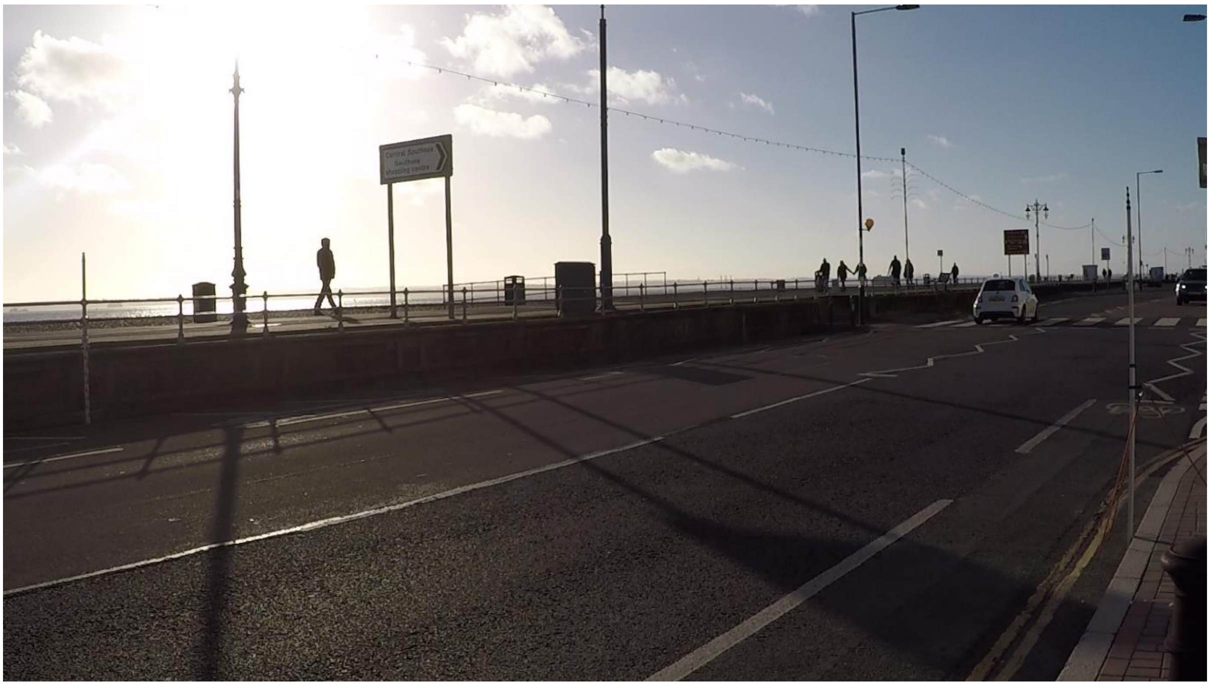
South Parade 94

South Parade 95

South Parade 96

South Parade 97

South Parade 98



South Parade 99

South Parade 100

Appendix E: Regression Models Output from SPSS

Generalized Linear Model Output of Objective 1

Model Information

Dependent Variable	Standard deviation (SD) of vehicle positions
Probability Distribution	Normal
Link Function	Identity

Case Processing Summary

	N	Percent
Included	98	100.0%
Excluded	0	0.0%
Total	98	100.0%

Categorical Variable Information

			N	Percent
Factor	Presence of parked vehicles	parked vehicles	24	24.5%
		no parked vehicles	74	75.5%
		Total	98	100.0%
	Presence of central reservation	present	33	33.7%
		not present	65	66.3%
		Total	98	100.0%
	Presence of nearside hatching	present	14	14.3%
		no present	84	85.7%
		Total	98	100.0%
	Presence of zigzag lines	present	13	13.3%
		not present	85	86.7%
		Total	98	100.0%
	Presence of cycle lanes	present	10	10.2%
		no present	88	89.8%
		Total	98	100.0%

Continuous Variable Information

		N	Minimum	Maximum	Mean	Std. Deviation
Dependent Variable	Standard deviation (SD) of vehicle positions	98	.1296298160	.8577157490	.450766058388	.1366563306631
Covariate	Lane Width in m	98	3.3989	14.1875	6.440638	1.8227007
	Road Width in m	98	5.500	22.700	14.68360	2.920581

Goodness of Fit[a]

	Value	df	Value/df
Deviance	.822	90	.009
Scaled Deviance	98.000	90	
Pearson Chi-Square	.822	90	.009
Scaled Pearson Chi-Square	98.000	90	
Log Likelihood[b]	95.231		
Akaike's Information Criterion (AIC)	-172.461		
Finite Sample Corrected AIC (AICC)	-170.416		
Bayesian Information Criterion (BIC)	-149.196		
Consistent AIC (CAIC)	-140.196		

Dependent Variable: Standard deviation (SD) of vehicle positions
Model: (Intercept), Presence of parked vehicles , Presence of central reservation, Presence of nearside hatching, Presence of zigzag lines, Presence of cycle lanes, Lane Width in m, Road Width in m
a. Information criteria are in smaller-is-better form.
b. The full log likelihood function is displayed and used in computing information criteria.

Omnibus Test[a]

Likelihood Ratio Chi-Square	df	Sig.
77.472	7	.000

Dependent Variable: Standard deviation (SD) of vehicle positions
Model: (Intercept), Presence of parked vehicles , Presence of central reservation, Presence of nearside hatching, Presence of zigzag lines, Presence of cycle lanes, Lane Width in m, Road Width in m
a. Compares the fitted model against the intercept-only model.

Tests of Model Effects

Source	Type III Wald Chi-Square	df	Sig.
(Intercept)	.168	1	.681
Presence of parked vehicles	.429	1	.512
Presence of central reservation	.441	1	.506
Presence of nearside hatching	.137	1	.711
Presence of zigzag lines	.695	1	.405
Presence of cycle lanes	2.775	1	.096
Lane Width in m	24.128	1	.000
Road Width in m	15.420	1	.000

Dependent Variable: Standard deviation (SD) of vehicle positions

Model: (Intercept), Presence of parked vehicles , Presence of central reservation, Presence of nearside hatching, Presence of zigzag lines, Presence of cycle lanes, Lane Width in m, Road Width in m

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	-.073	.0648	-.200	.055	1.252	1	.263
[Presence of parked vehicles =1.00]	.016	.0245	-.032	.064	.429	1	.512
[Presence of parked vehicles =2.00]	0[a]	.	.	.	.	.	.
[Presence of central reservation=1.00]	-.014	.0217	-.057	.028	.441	1	.506
[Presence of central reservation=2.00]	0[a]	.	.	.	.	.	.
[Presence of nearside hatching=1.00]	.010	.0283	-.045	.066	.137	1	.711
[Presence of nearside hatching=2.00]	0[a]	.	.	.	.	.	.
[Presence of zigzag lines=1.00]	.026	.0306	-.034	.086	.695	1	.405
[Presence of zigzag lines=2.00]	0[a]	.	.	.	.	.	.
[Presence of cycle lanes=1.00]	.061	.0368	-.011	.133	2.775	1	.096
[Presence of cycle lanes=2.00]	0[a]	.	.	.	.	.	.
Lane Width in m	.035	.0071	.021	.049	24.128	1	.000
Road Width in m	.020	.0050	.010	.030	15.420	1	.000
(Scale)	.008[b]	.0012	.006	.011			

Dependent Variable: Standard deviation (SD) of vehicle positions

Model: (Intercept), Presence of parked vehicles , Presence of central reservation, Presence of nearside hatching, Presence of zigzag lines, Presence of cycle lanes, Lane Width in m, Road Width in m

a. Set to zero because this parameter is redundant.

b. Maximum likelihood estimate.

Linear Model Output of Objective 2

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Camber of the road [%], Standard deviation (SD) of vehicle positions, Lane[b]	.	Enter

a. Dependent Variable: Nearside rut depth [mm]

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.566[a]	.320	.299	1.08614

a. Predictors: (Constant), Camber of the road [%], Standard deviation (SD) of vehicle positions, Lane

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	52.297	3	17.432	14.777	.000[b]
	Residual	110.893	94	1.180		
	Total	163.190	97			

a. Dependent Variable: Nearside rut depth [mm]

b. Predictors: (Constant), Camber of the road [%], Standard deviation (SD) of vehicle positions, Lane

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.014	.731		-1.386	.169
	Standard deviation (SD) of vehicle positions	-1.881	.808	-.198	-2.328	.022
	Lane	1.633	.273	.633	5.987	.000
	Camber of the road [%]	.396	.087	.484	4.574	.000

a. Dependent Variable: Nearside rut depth [mm]

An alternative approach to Linear Model Output of Objective 3

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Lane, Lane Width in m, Camber of the road as a percentage, Road Width in m[b]	.	Enter

a. Dependent Variable: Rut depth in mm (LEFT)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.560[a]	.314	.284	1.09736

a. Predictors: (Constant), Lane, Lane Width in m, Camber of the road as a percentage, Road Width in m

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	51.198	4	12.800	10.629	.000[b]
	Residual	111.991	93	1.204		
	Total	163.190	97			

a. Dependent Variable: Rut depth in mm (LEFT)

b. Predictors: (Constant), Lane, Lane Width in m, Camber of the road as a percentage, Road Width in m

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.568	.902		-.630	.530
	Lane Width in m	.023	.083	.032	.274	.785
	Road Width in m	-.091	.053	-.204	-1.726	.088
	Camber of the road as a percentage	.367	.090	.448	4.099	.000
	Lane	1.621	.276	.628	5.868	.000

a. Dependent Variable: Rut depth in mm (LEFT)

FORM UPR16

Research Ethics Review Checklist

Please include this completed form as an appendix to your thesis (see the Research Degrees Operational Handbook for more information

UNIVERSITY OF PORTSMOUTH

Postgraduate Research Student (PGRS) Information		**Student ID:**	848686
PGRS Name:	Renan Sinanmis		
Department:	SCES	**First Supervisor:**	Dr Lee Woods
Start Date: (or progression date for Prof Doc students)	01/02/2017		
Study Mode and Route:	Part-time ☐ Full-time ☒	MPhil ☐ PhD ☒	MD ☐ Professional Doctorate ☐

Title of Thesis:	Traffic channelisation and pavement deterioration: An investigation of the lateral wander on asphalt pavement rutting
Thesis Word Count: (excluding ancillary data)	35251

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES ☒ NO ☐
b) Have all contributions to knowledge been acknowledged?	YES ☒ NO ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES ☒ NO ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES ☒ NO ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES ☒ NO ☐

Candidate Statement:	
I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)	
Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	92C7-A6A7-A733-1372-1042-B2B4-0EE2-0724
If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:	
Signed *(PGRS)*: Renan	**Date:** 21/07/2020

UPR16 – April 2018